AD 682023

Special Technical Report 49

THE COUNTING OF LIGHTNING FLASHES

By: E. T. PIERCE

Prepared for:

U.S. ARMY ELECTRONICS COMMAND
FORT MONMOUTH, NEW JERSEY 07703

CONTRACT DA 36-039 AMC-00040(E)
ORDER NO. 5384-PM-63-91

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June 1968

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ABSTRACT

The principles involved in using lightning-flash counters are first discussed, with especial reference to the ERA and CCIR types of counter. The concept of an effective range is introduced, and it is shown how the value obtained for the effective range is influenced by counter sensitivity and by the amplitude distribution of the lightning-generated signals at the thunderstorm source.

The results obtained at two sites in Thailand with ERA and CCIR counters are presented, analyzed, and compared with data for Singapore. It is established that during months of high thunderstorm incidence the lightning - flash density is proportional to the square of the well-known thunderstorm-day parameter; ~~the~~ for low-activity months, the proportionality is direct. The transition between the two laws occurs when the number of thunderstorm days per month, T_m, is about three. Over most of Thailand T_m always exceeds 3 except during the months of December through February.

Seasonal and diurnal variational patterns in lightning incidence are derived. Monthly changes are related, as indicated above, to the T_m statistic. As regards diurnal variation, from March to June thunderstorms tend to break out in the local afternoon; later in the year the peak activity moves to the early evening and night hours.

It is demonstrated that the occurrence of a nearby thunderstorm increases received atmospheric noise power--for example, by some 10 to 20 dB at MF.

Finally, comparisons of the data from the ERA and CCIR counters demonstrate that the former design is superior in precision as an indicator of local thundery activity. The CCIR type of counter has an inherent propensity to respond to the larger impulses generated in distant thunderstorms; this effect becomes increasingly pronounced as the counter sensitivity is increased.

PREFACE

The work described in this report was performed with the support, and using the facilities, of the Military Research and Development Center (MRDC) in Bangkok, Thailand. The MRDC is a joint Thai-U.S. organization established to conduct research and development work in the tropical environment. The overall direction of the U.S. portion of the MRDC has been assigned to the Advanced Research Projects Agency (ARPA) of the U.S. Department of Defense who, in 1962, asked the U.S. Army Electronics Command (USAECOM) and the Stanford Research Institute (SRI) to establish an electronics laboratory in Thailand to facilitate the study of radio communications in the tropics and related topics. The MRDC-Electronics Laboratory (MRDC-EL) began operation in 1963 [under Contract DA 36-039 AMC-00040(E)] and since that time ARPA has actively monitored and directed the efforts of USAECOM and SRI. In Bangkok, this function is carried out by the ARPA Research and Development Field Unit (RDFU-T). The cooperation of the Thai Ministry of Defense and the Thailand and CONUS representatives of the ARPA and USAECOM made possible the work presented in this report. Special acknowledgment is due to the Thai Meteorological Department, which for most of the period of this report was administered by the Royal Thai Navy, for their courtesy in supplying thunderstorm day information.

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ACKNOWLEDGMENTS

Mr. Rangsit Chindahporn was principally responsible, under the supervision of Mr. R. E. Leo and, subsequently, Mr. E. Leroy Younker, for collecting the data examined in this report. The author is very grateful to all these gentlemen; if the data had not been available this report would not have been written. During its preparation Mr. G. H. Hagn made many suggestions that were most helpful.

Finally, it is a pleasure to thank Professor S. A. Prentice for his loan of an ERA-type counter.

I INTRODUCTION

There are two separate groups of scientists interested in the counting of lightning flashes, each with different objectives. Electrical engineers engaged in the construction of surface power lines need to decide what measures--if any--of protection from lightning strikes are desirable. The cost of installing various kinds of protective devices has to be balanced against the likelihood of strikes. Accordingly, knowledge of the incidence of lightning at localities throughout the world is desirable, and it is hoped that the use of lightning-flash counters will improve this knowledge.

Radio engineers are troubled by radio noise generated by lightning flashes, which interfere with radio communications. In order to estimate the interference, information on global thunderstorm activity is necessary. Again, lightning-flash counters can assist in supplying this information.

Both electrical and radio engineers have based much of their past work upon the meteorological statistic of the thunderstorm day. This is an observational day during which thunder is heard; it is noted as a routine at most meteorological stations. Although the thunderstorm-day statistic is useful, its applicability is limited; there is no indication, for example, of the violence of the activity on a day with thunder. This type of information is potentially available from lightning-flash counters. One distinction between the requirements of the radio and of the electrical engineers is noteworthy. Radio noise is generated by all kinds of lightning flashes but only discharges to earth are involved in the protection of power lines.

It may seem surprising that meteorologists have not been included in the categories of scientists given above. However, it must be admitted that meteorologists, lacking perhaps the practical economic stimuli of the radio and electrical engineers, have shown relatively little interest in counting flashes. There are signs that this attitude is changing.

Certainly counters can be a useful adjunct both to local meteorological research and to wider-scale synoptic investigations.

Lightning-flash counters have been constructed, installed, and operated in Thailand under the radio-noise section of the general research program on tropical radio communication organized by the Military Research and Development Center (MRDC). In a tropical country such as Thailand, radio noise has two main components. There is the high background due to noise signals propagated from the major centers of thunderstorm activity. This noise, although sufficiently strong to be a nuisance in radio work, is never intense enough, given modern equipment design, to seriously disrupt communication. Furthermore, knowledge of the general noise background is reasonably well established, and predictions of levels can be made within fairly narrow limits as a result of the work organized by the International Radio Consultative Committee (CCIR)[1].* These predictions are still capable, however, of being improved; this is demonstrated by the work reported in another[2] of the Special Technical Reports in this series.

The second component of the noise is that due to local thundery activity. This is not so well defined or understood as the background noise, although nearby thunderstorms can certainly eliminate radio communications to an extent that can never be achieved by more distant activity. The main objective of the lightning-flash counter work in conjunction with noise recordings[2] of the ARN-3 type was to better establish the characteristics of the disturbance caused by local thunderstorms. The ARN-3 records show the noise effects, and the simultaneous flash counter data indicate the strength and proximity of the adjacent activity. A second objective of the lightning-flash counter work was to assess the relationship between local thunderstorm intensity and such long-term climatological parameters as the thunderstorm day, or the thunderstorm and lightning day. It was hoped that this long-term information could

* References are listed at the end of the report.

then be applied in predictions of the noise component due to local thunderstorms. A third objective was to use the counter data so as to establish some basic thunderstorm information for Thailand--e.g., distribution, through the day, of flashing rates, variation with season, etc.

Some of the work described in this report has already been partly discussed in certain of the Semiannual Reports published under this project.[3,4,5,6,7] The discussion is repeated here to provide an overall view of the flash-counting program. This Special Technical Report (STR) is complementary to certain aspects of the research reported in STR 37[2] and STR 47.[8] Parts of these two reports deal in particular with the increase in radio noise, as detected by various types of antenna, associated with the occurrence of local thunderstorms.

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II BASIC CONCEPTS IN LIGHTNING-FLASH-COUNTER DESIGN

Many designs of lightning-flash counters have been proposed, constructed, and operated; the main difference between the individual designs is in the frequency band over which the counter functions. Counters generally have the common feature that they trigger when the change in electric field at the location of the counter, due to a lightning flash, exceeds a certain threshold E_T. This threshold can in practice be adjusted by changing antenna configurations, varying counter sensitivity, and so on.

Suppose a thunderstorm is active at a distance d from the site of the counter. The field-change impulses that operate the counter have a certain original amplitude distribution at the thunderstorm source, while the amplitudes are diminished by propagational attenuation. Thus, the percentage P of flashes in the thunderstorm for which the counter functions can be expressed in some form such as

$$P = \int_{E_{Td}}^{\infty} F(E) \cdot dE \text{ , where } E_{Td}\varphi(d) = E_T \quad . \qquad (1)$$

In Eq. (1) the function F(E) represents the source amplitude distribution expressed relative to some quantity such as the median amplitude M. The attenuation during propagation is indicated by the distance-dependent function $\varphi(d)$; note that $\varphi(d)$ does not necessarily or even probably have the same form for all ranges of d.

A. The Effective Range of a Counter

The effective range R of a lightning-flash counter has been considered by Pierce[9] and Horner[10] to be the distance within which the actual number of flashes occurring, when observed over a lengthy period of time, is equal to the number counted. Because the amplitudes of the signals at the lightning flash source are not the same, some of the flashes originating from a distance greater than R will be counted, while others for which $d < R$ will not operate the counter. The definition of effective range implies that when considered on a long-term basis, thundery activity is uniform over distances comparable with R. This concept has been criticized by Brook and Kitagawa.[11] Their criticism is, however, perhaps biased by their experience in the unusual conditions of New Mexico, U.S. Here there is a very strong tendency for thunderstorms to form over isolated mountain peaks, thus leading, even on a long-term basis, to a very uneven geographical distribution of storm activity. This pronounced orographic control is not common meteorologically. Most thunderstorms are initiated by atmospheric instabilities largely unrelated to surface conditions; hence such common designations as air-mass, frontal, and squall-line thunderstorms. It is the practice with most types of counter to set E_T so that R is some 10 to 30 km. An examination of average annual thunderstorm-day maps for such characteristic temperate and tropical areas as Britain and Thailand shows no evidence of drastic variations in thunderstorm occurrence over distances of the order of 30 km. Hence it is concluded that the definition of effective range is appropriate for most parts of the world, but may--as Brook and Kitagawa have indicated--be inapplicable where orographic or other influences cause thunderstorm occurrence to be extremely non-uniform.

The vertical electric field E at the surface of the earth at a distance d from a flash is given approximately, in rationalized MKS units, by

$$E = \frac{1}{4\pi\epsilon_o}\left(\frac{S}{d^3} + \frac{1}{cd^2}\cdot\frac{dS}{dt} + \frac{1}{c^2 d}\cdot\frac{d^2S}{dt^2}\right) \quad . \tag{2}$$

In Eq. (2), which is essentially the conventional dipole treatment, c is the velocity of light; t represents time; ϵ_o is the permittivity of free space $[(36\pi \times 10^9)^{-1}]$; while S, the electric moment of a thundercloud, is defined by $2\,\Sigma\, qh$, q and h being the charge and height, respectively, of a small charged element in the thundercloud, with the summation extending over all charges associated with the cloud. The three terms in Eq. (2) are usually known as the "electrostatic," the "induction," and the "radiation" components. Simple differentiation shows that for a given frequency f they are equal when $d = d_f = c/2\pi f$; within this critical value the electrostatic term is dominant, while for $d > d_f$ the radiation term is the largest. For f = 500 Hz, $d_f \approx 100$ km; at 10 kHz, $d_f \approx 5$ km.

Equation (2) can be applied with profit to the field change associated with a lightning flash. Essentially the equation considers d to be large compared with the height of the thundercloud, and regards the discharge as a vertical radiating antenna, of dimensions small compared with a wavelength, and situated in free space above a flat, perfectly conducting earth; the equation therefore has its limitations. Errors are increasingly pronounced as frequencies become greater, as the influence of earth curvature enters significantly, as signals beginning to be appreciable compared with those of a ground wave are returned from the ionosphere, and as ground conductivity becomes poorer. Most of these effects are more important at the greater distances and have their main influence on the radiation term. However, the approximation implicit in Eq. (2)--considering the thunderstorm altitude as small compared with d--is, of course, least valid for close distances.

Counters as already mentioned usually trigger on a threshold level E_T and are non-operative for signals below this level. The threshold can be related to an effective range, provided the variation with distance of the lightning signals covering the frequency acceptance band of the counter is known. Alternatively--and more directly--an effective range can be obtained by merely comparing counter readings with visual and other reports positioning lightning and thunderstorm activity.

If all discharges were identical, a counter would respond to every flash occurring within the effective range and ignore all activity at greater distances. However, this ideal result cannot be achieved since individual lightning flashes differ very considerably in their characteristics. Generally speaking, the indeterminacy of range increases with increasing frequency and then diminishes. At extremely low frequencies, the electrostatic term of Eq. (2) is dominant and--due to the approximate inverse cube variation with distance--the range is well defined. As frequency increases, the dominance moves to the radiation component which has only an inverse distance dependence; furthermore, as frequency continues to rise, fields reflected from the ionosphere become more important and the change with distance is not even as pronounced as a linear inverse law. Thus the range indeterminacy becomes large. Ultimately, for very high frequencies, which penetrate the ionosphere, propagation is almost by line-of-sight, and therefore sharply limited by earth curvature.

A quantitative example is useful in illustrating the uncertainties involved in defining the range of a counter. Figure 1 shows calculations of the median signal strength versus distance for the first return stroke of a flash to earth (this, of course, is only part of the complete signal from a discharge to ground). Curves for the two frequencies of 500 Hz and 10 kHz are given in Fig. 1; these frequencies lie within the respective bands at which the British Electrical Research Association (ERA) and the CCIR counters--the two most common types--operate. The curves of Fig. 1 reflect the relative change of importance with distance of the three terms in Eq. (1); a correction was incorporated in the calculations to include the contribution, at larger distances, of components returned from the ionosphere. Because d_f is much greater for 500 Hz than it is for 10 kHz, the curves differ considerably in slope.

Most measurements (discussed in greater detail later) show that the amplitudes of the signals from lightning flashes follow a log-normal distribution [the function F(E) of Eq. (1)]. The standard deviation of the distribution, with the individual signals, E, expressed relative to the median, M, in decibels (20 log E/M), is about 6 dB. Thus some 90 percent of the signals will be within 10 dB of M--that is, between the approximate limits of 3 M and 0.3 M. These limits (±10 dB) represent one division of the vertical logarithmic scale of Fig. 1. The intended range of most lightning flash counters is "local" and perhaps comparable with that involved in the thunderstorm day statistic; it is in the order, therefore, of tens of kilometers. Suppose the threshold is set to the median signal appropriate to a distance of 30 km. Then Fig. 1 indicates

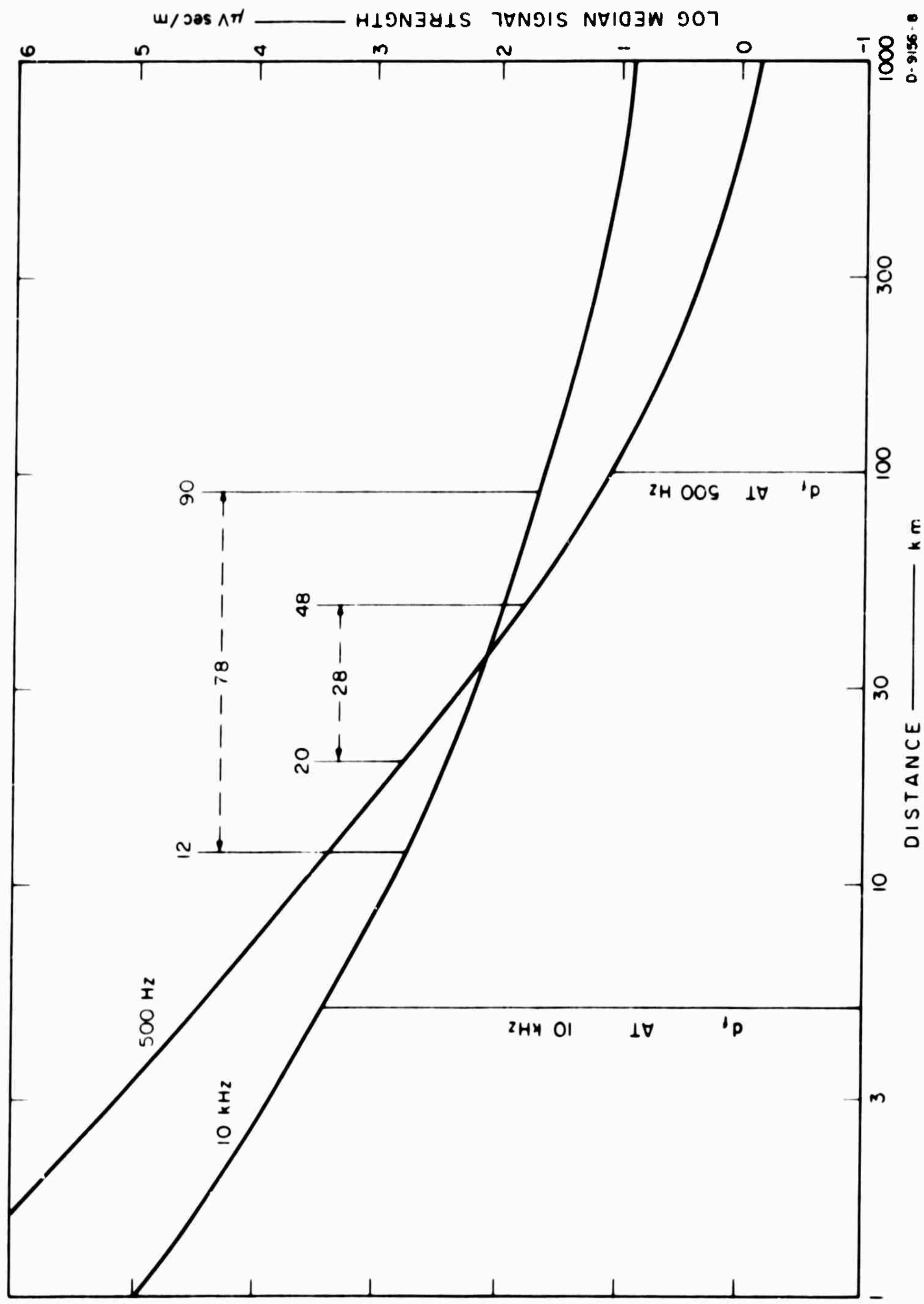

FIG 1 MEDIAN SIGNAL STRENGTH vs DISTANCE FOR A FIRST RETURN STROKE

that at 500 Hz a 10-dB deviation from M corresponds to a distance range of 20 to 48 km; for 10 kHz the same deviation gives 12 to 90 km. Thus the range of a lightning-flash counter is always a somewhat imprecise concept, and is more indeterminate at 10 kHz than at 500 Hz. However, this imprecision is not serious as regards synoptic investigations, on a global scale, of radio noise and thundery activity. Extremely valuable information can be obtained by comparing the readings of similar counters sited in different localities. Accurate range estimates are necessary only if results are to be expressed in terms of a parameter such as flashes to earth per square kilometer per annum. This parameter, incidentally, is much favored by electrical engineers.

B. Specific Types of Counter

There are many designs of lightning-flash counters in existence; two of these--the CCIR and ERA types--have been extensively developed and employed. Others, including, for example, the Malan and Sonde instruments, are still under development or have not been widely used.

No lightning-flash counter is entirely satisfactory in its performance. Nor, in view of the intrinsic variability of the discharge, is it likely that perfection will ever be achieved. As Brook and Kitagawa[11] have pointed out, it cannot be over-emphasized that a counter is not a precise indicator. This does not mean that counters are of little use; on the contrary, the results that they yield can be of great value. However, care and intelligence must constantly be employed in the installation, supervision, and data interpretation associated with lightning flash counters. Readings should not be blindly accepted at face value; this is particularly so for results from an isolated counter.

1. The CCIR Counter

The development of this counter (Horner[10]) has an interesting history. The Consultative Committee for International Radio (CCIR), feeling that the thunderstorm-day parameter was unsatisfactory for the purpose of predicting radio noise, suggested to the World Meteorological Organization (WMO) that they should encourage the use of lightning-flash counters. The riposte by WMO was favorable, provided CCIR developed a suitable counter design. The design that eventually emerged, from an original by Sullivan and Wells,[12] is termed the CCIR (sometimes WMO) counter. It is a wideband device operating--broadly speaking--within the VLF frequency range. The exact frequency coverage depends upon the details of the antenna system, but with typical installations the peak response is at 10 kHz and the 6-dB points are at about 1.5 and 40 kHz. Although there is no conscious attempt to distinguish between cloud and ground discharges, a certain effective discrimination exists since ground flashes produce signals perhaps ten times as large as discharges in the cloud over the frequencies concerned. The triggering threshold is usually set for a strength corresponding to the median amplitude signal from a distance of about 20 km. However, because the counter is operating on the radiation field, the change of signal strength with distance is so slow (see Fig. 1) that an effective range is not precisely defined; and the distance for which 50% of flashes produce counter functioning is certainly not to be identified as the effective range.

The CCIR counter essentially registers radio noise and so fulfills the implicit objective intended by CCIR. However, since the counter often responds to signals of very distant origin, it generally is difficult to relate its readings to the fundamentally local statistic of the thunderstorm day.

2. The ERA Counter

The original of this instrument was suggested by Pierce,[9] developed commercially by Golde and others of the British Electrical Research Association (ERA), and has had many improvements made subsequently--notably by Müller-Hillebrand[13] and Barham.[14] The frequency coverage (6 dB points) is about 200 Hz to 2 kHz, while the maximum operating range is some 40 km. Thus the operation is dominantly on the electrostatic component. The counter is intended to operate preferentially on discharges to ground. The discrimination against cloud flashes is obtained in two ways. Firstly, the counter accepts only positive impulses. The total electrostatic field change is positive at all distances for the great majority of discharges to ground; for most cloud flashes, however, the changes are positive only within 10 km and negative at greater ranges. The second discriminant is in the frequency response. Ground flashes have large sudden electrostatic field charges associated with return strokes; these are absent for cloud discharges. The frequency passband of the ERA counter is centered at about 600 Hz; at this frequency the electrostatic fields accompanying return strokes have large components, but flashes in the cloud produce only weak signals. Thus there is an effective discrimination.

3. <u>Other Counters</u>

There are many designs of counters, but two recent types are especially interesting. The Malan[15] counter is particularly intended to differentiate between ground and cloud flashes. It contains two channels tuned respectively to 5 and 100 kHz. At 100 kHz, experiments show that the noise emitted by cloud and ground flashes is about equal; at 5 kHz, on the other hand, the signal from a ground discharge is perhaps ten times as great as that from a cloud flash. The circuitry uses this fact to distinguish between the two kinds of flashes for an operating range of about 10 km. Only pilot versions of the Malan counter have been tried. The question of errors caused by the departure of individual flashes from the average pattern has not yet been seriously considered.

Sonde[16] has developed a counter that operates at a frequency of 3 MHz and with a bandwidth of 10 kHz (6-dB points). At 3 MHz the signals from cloud and ground flashes are similar in characteristics; there is therefore no discrimination between the types of discharge. The triggering threshold is set for a nominal range of 20 km. Systematic comparison of the operation of this counter with that of other designs, and with recordings of field variations, would be of interest. The Sonde counter has been employed by Aiya[17] in a series of comprehensive measurements in India.

C. Tests of Counters

Only he CCIR and ERA types of counter have been very widely used and have had their performance critically examined. Both counters have deficiencies but, as already mentioned, a perfect instrument is unattainable. Some investigators have obtained better results with the CCIR than with the ERA counter; others have had the opposite experience. Generally speaking, there has been a comprehensible tendency for research workers to prefer the counter with whose development they h ve been most closely associated.

The CCIR counter, as already indicated, accepts signals of very distant origin; this is especially so at night. Accordingly, the relation to local thundery activity is not well marked, and the range of the counter is poorly defined. The counter is perhaps better described as counting atmospherics rather than lightning flashes.

The main deficiency of the very simple ERA counter is that the discrimination between cloud and ground flashes is insufficiently definite. This is because, since the original design of counter, it has been discovered that cloud discharges usually contain small, fairly abrupt field-changes of either polarity. These are somewhat similar to the variations accompanying very weak return strokes, and can therefore actuate an ERA counter under some circumstances.[18] Extensive investigations have shown that corrections for the number of cloud flashes counted can be established, and that the correction diminishes if the counter sensitivity (and consequently range) is reduced. Reduction of sensitivity also decreases spurious actuation of the counter by internal instabilities.

D. Research Programs with Counters

Although counters have been widely used, there have been few investigations aimed at determining to what extent counters do, in practice, perform as intended and claimed by their designers. Such topics as the relative number of cloud and ground flashes counted, the influence of sensitivity, the proportions of discharges originating at various ranges that are recorded, and so on, still need much clarification. A great deal remains to be done in spite of the valuable work by, in particular, Müller-Hillebrand, Mackerras, and Horner.

A research program in lightning flash counting can be very modest or elaborated to an almost unlimited extent. The first step is to set up and operate a counter according to the instructions for the particular type selected. The results should be correlated with sightings of lightning and the hearing of thunder; even this simple procedure is very productive. It is especially useful when a counter is first installed, since a rough effective range can thus be very quickly determined. After this has been done, the counter sensitivity should be varied and the results compared with observations of lightning and thunder. In this way a calibration of sensitivity versus range can be established. More elaborate information on thunderstorm location may be available. This can come from extensive meteorological networks, radar surveillance, or radio direction finders; any such sources should be fully utilized.

It is obviously of great interest to operate different types of counters at the same site simultaneously, and to compare their responses. Correlation can also be made with records of integrated radio noise at different frequencies, and with electric field observations.

Ideally, tests of counter operation should be made by comparing the triggering of the counter against a continuous record of field variations within the frequency acceptance band of the counter. This procedure becomes complicated, especially for counters operating at the higher frequencies. With Sonde's counter, for example, a record of a considerable time resolution might be required for a period of perhaps one hour--a formidable undertaking.

In general, however, a broadband record of field variations within the frequency range of 3 to 100 Hz is a very useful adjunct to investigations with any type of counter. The field changes are electrostatic, the total alteration accompanying a discharge is an approximate indication of the range, and a time resolution of ten milliseconds enables the variations associated with return strokes--and consequently flashes to earth--to be identified. The electrostatic record could be derived from a field mill, or by an antenna sensor, using magnetic tape or a photographed oscilloscope for recording.

Experiments with networks of counters spaced so that their ranges overlap can obviously provide valuable synoptic information over wide geographical areas. The limits of such investigations are controlled by economic rather than by technical considerations. In this connection, it is perhaps interesting to note that there are considerable differences in the complexity--and therefore the construction cost--of the counters. The order, in terms of increasing expense, is ERA, CCIR, Sonde, Malan; a rough corresponding estimate of the proportionate cost is 1:3:6:10.

E. The Amplitude Distribution (AD) at the Source

It is generally agreed that the amplitudes of lightning signals when expressed in decibels follow a normal law. As Aiya[19] has pointed out, the log-normal distribution applies to many thunderstorm parameters, and is indeed inevitable if the variability of the parameter arises from the combination of many statistically independent processes. Horner and Bradley[20] have presented data on the variability, as a function of frequency, of the peak signal amplitude attained during a lightning discharge. Since the average duration of a flash is appreciably less than a second, and the "dead time" after triggering of the various counters is usually more than this, the peak signal amplitude in a discharge is that effective in operating a counter.

At MF and HF, Horner and Bradley find that the standard deviation σ of the log-normal distribution obeyed by the peak amplitudes from a single storm is about 4.5 dB. When the variations between individual storms are also included, σ increases to about 6 dB (Horner[21]).

At VLF, the work of Horner and Bradley shows that the log-normal distribution applies, but with a standard deviation σ of about 6 dB for individual storms and 8 dB for all storms; this latter is significantly more than the 6 dB found at HF. Horner and Bradley consider that this larger value of σ is because the atmospherics from cloud and ground discharges are less similar at VLF than at HF. Although this distinction is certainly true, there is considerable evidence (Horner,[21] and Dennis and Pierce[22]) that the standard deviation approaches 8 dB even when only the VLF atmospherics associated with the return strokes of flashes to earth are considered.

When the source impulses obey the log-normal law, F(E) in Eq. (1) may be written as

$$F(E) = \frac{100}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(E - M)^2}{2\sigma^2}\right] \tag{3}$$

where E and σ are in decibels relative to the median amplitude M.

1. Application of AD to Effective Range of CCIR Counter

Since the CCIR instrument is a broadband device, it is not easy to establish the field strengths, as a function of distance, effective in operating the counter. The counter threshold E_T is normally set by reference to a step voltage V_T applied through a calibrator; 3-, 5-, and 10-volt settings are commonly used with the standard 7-m antenna. Horner[10] considers that fo. a thunderstorm at the effective range R of the counter, some 25% of the flashes in that storm trigger the counter. He also finds that during widespread thundery activity with V_T set at 3 and 10 V, 25% of discharges are counted when the amplitudes in a bandwidth of 300 Hz at 10 kHz (about the midpoint of the pass band for the CCIR counter) are 150 mV/m and 450 mV/m respectively. Horner and Bradley[20] give the median value of peak field strength at 10 kHz (in a bandwidth of 250 Hz and for a distance of 10 km) as 500 mV/m; if the standard deviation of the log-normal amplitude distribution is taken as 8 dB it follows that 25% of the signals exceed about 950 mV/m. Then, assuming a proportionality to bandwidth and an inverse distance law of amplitude variation, values of 3 V and 10 V respectively for V_T should correspond--with the standard 7-m antenna--to effective ranges, respectively, of 76 [= (950/150)(300/250)10] and 25 km. If the standard deviation is taken as 6 dB, 25% of the signals exceed 1.6 M (approximately); the estimates of effective range for V_T = 3 and 10 V then become 64 and 21 km.

As another way of estimating the effective range, R, we may adopt another observation by Horner.[10] This is that with $V_T = 3$ V, the CCIR counter triggers when the field strength of the incoming atmospherics, as measured over the broad VLF band of 1 to 25 kHz, is 3 V/m. The early work of Appleton and Chapman[23] indicates radiation fields of this magnitude as coming from storms at a distance of 60 km, while the analysis of Dennis and Pierce[22] suggests 80 km; thus the effective range of $V_T = 3$ V should be approximately 70 km.

As yet another way of determining effective range we consider the spectral component at 10 kHz; this is given as 1000 μV sec/m at 10 km by Horner and Bradley,[20] and as 50 μV sec/m at 100 km by Dennis and Pierce.[22] Converting according to inverse distance and bandwidth proportionality yields 250 mV/m and 125 mV/m at 10 km for 250 Hz bandwidth at 10 kHz; this may be compared with the 500 mV/m quoted in the first paragraph of this section. Repeating the analysis of that paragraph, and taking account of two possible values (6 dB and 8 dB) for the standard deviation, we obtain four estimates of R for each of the two triggering thresholds: these estimates are 19, 38, 16, and 32 km for $V_T = 3$ V, and 6, 13, 5, and 11 km for $V_T = 10$ V.

Finally, it should be mentioned that Müller-Hillebrand considers the effective range of the CCIR counter for $V_T = 3$ V to be about 110 km. Also in a recent paper Horner[24] estimates that with the standard 7-m antenna the effective ranges for $V_T = 3$ and 10 V were, respectively 30 km and 9 km; in 1960 Horner's estimates were 30 km and 13 km.

The very confusing information of the preceding paragraphs is conflicting and sometimes lacking even in self-consistency. It effectively demonstrates, however, the difficulties involved in accurately assessing an effective range for the CCIR-type lightning flash counter. To summarize, with $V_T = 3$ V we have estimates for R of 16, 19, 30, 32, 38, 64, 70, 76 and 110; for $V_T = 10$ V the estimates are 5, 6, 9, 11, 13, 13, 21, and 25! Since ideally the distance dependence of field-strength follows an inverse law for the CCIR counter the geometric mean is the most appropriate way of averaging the above results; hence, we have $R \approx 10$ km for $V_T = 10$ V, and $R \approx 40$ km for $V_T = 3$ V.

2. Application of AD to Effective Range of ERA Counter

As already discussed (Sec. II-A and Fig. 1) the frequency and distance coverage of this counter should mean that the range estimation is more precise than for the CCIR instrument. Both theoretical and experimental work suggest that this is indeed so, but the uncertainties involved are still considerable. Even when the antenna arrangements and nominal sensitivity of the counter have been the same, the estimates of effective range differ widely; this is partly because some of the ways adopted for estimating the range are of very dubious validity. The conventional mode of operation of an ERA counter is with a standard antenna of 5 m effective height, of some 220 pF capacitance, and with the sensitivity adjusted to respond to a step change in the atmospheric electric field of 5 V/m (E_T). For a storm at a specific distance the percentages of intracloud and cloud-ground discharges triggering the counter will be the same only at very short distances (both 100%) or at large distances (both 0%). At intermediate distances cloud-ground flashes will be more effective than intracloud discharges in operating the counter, but the effects of the latter type of flash are still important.

Prentice[25] has given an excellent survey of the uncertainties involved in assessing the range of the ERA-type of counter; this survey was prepared for a study committee of the Comité International des Grandes Reseaux Electriques (CIGRE). In his paper Prentice considers estimates of R deduced both experimentally and theoretically. Some of the latter analyses are based on a use of the log-normal law; in this instance the application is to the distribution of peak currents in return strokes. Prentice points out that for a given counter setting the effective ranges defined for cloud-ground, R_g, and intracloud discharges, R_c, will be different. With the standard arrangements discussed above, the many sources of evidence fall within the limits given by $12.5 \leq R_g < 38$ and $8 \leq R_c < 25$, where R_g and R_c are in km. The best estimates to adopt are probably those of Bunn[26]--namely, $R_g \approx 30$ km and $R_c \approx 20$ km. With these effective ranges almost all intracloud flashes are counted for distances of less than

10 km while few are registered from beyond 25 km; for cloud-ground discharges the corresponding distances are 25 and 50 km.

3. A Comment on the Sonde Counter

Sonde[16] estimates the range of his counter to be 20 km. The counter is set to trigger when E_T = 200 μV/m; this field strength applies over the counter bandwidth of 10 kHz centered at 3 MHz. Horner and Bradley[20] indicate some 1500 μV/m as being the median value of peak field strength at 3 MHz, for a bandwidth of 250 Hz, at a distance of 10 km from a thunderstorm. If this is converted to d = 20 km and a bandwidth of 10 kHz on the basis of inverse distance and square root of bandwidth laws, the resulting field strength is about 5 mV/m; this is approximately 25 times the value of E_T considered by Sonde as appropriate for a range of 20 km. We have thus a serious discrepancy and yet another example of the uncertainties involved in estimating counter ranges.

In one respect Sonde's work confirms previous results. He implies that at a distance of 30 km the field strength in the acceptance band of his counter generally exceeds 200 μV/m but is rarely greater than 1 mV/m. If we take the median field strength as the approximate geometric mean 450 μV/m, then with a standard deviation of 6 dB some 80% of discharges give fields of more than 200 μV/m, but only about 12% yield fields in excess of 1 mV/m. Thus a log-normal distribution with a standard deviation of 6 dB is reasonably compatible with Sonde's experience.

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III THE RESULTS FROM THE CCIR-TYPE COUNTER AT BANGKOK

This counter first started to obtain data in May 1964 and has continued to operate through October 1967, and subsequently.* There have been occasional periods, due to equipment failures or other causes, when the counter has been inactive, but these have not been extensive. Thus the data represent a valuable long-term record.

The threshold voltage V_T for the Bangkok counter was set at 6 V while the antenna employed was a vertical whip 5 m long. The work of Horner[10,24] previously discussed, suggests that with these characteristics the counter should have an effective range, R, of between 10 and 15 km. An independent and more basic estimate of the effective range is presented in Appendix A; the result is that $R \approx 11$ km. The agreement between the "Horner" and the independent estimate is remarkable, particularly since the exposure of the Bangkok antenna was not ideal.

A. Seasonal and Monthly Data

The mean daily count per month, D_m, is plotted in Fig. 2 for the period from May 1964 to October 1967. This parameter is selected rather than the total monthly count since there were occasional days when the counter was not in operation and a listing of monthly aggregates would therefore be misleading. Also plotted in Fig. 2 are the average monthly values of the thunderstorm-day, T_m, statistic and thunder/lightning-day statistic. These are for the period 1948-1957 and were determined by the Thai Meteorological Department.

The three graphs of Fig. 2 should not be closely correlated since even for the same month D_m varies very considerably from year to year.

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* Only the data between May 1964 and October 1967 inclusive are considered in this report. During this period the major intervals when the counter was inoperative were July and August 1966, and the months of January, February, March, and April 1967.

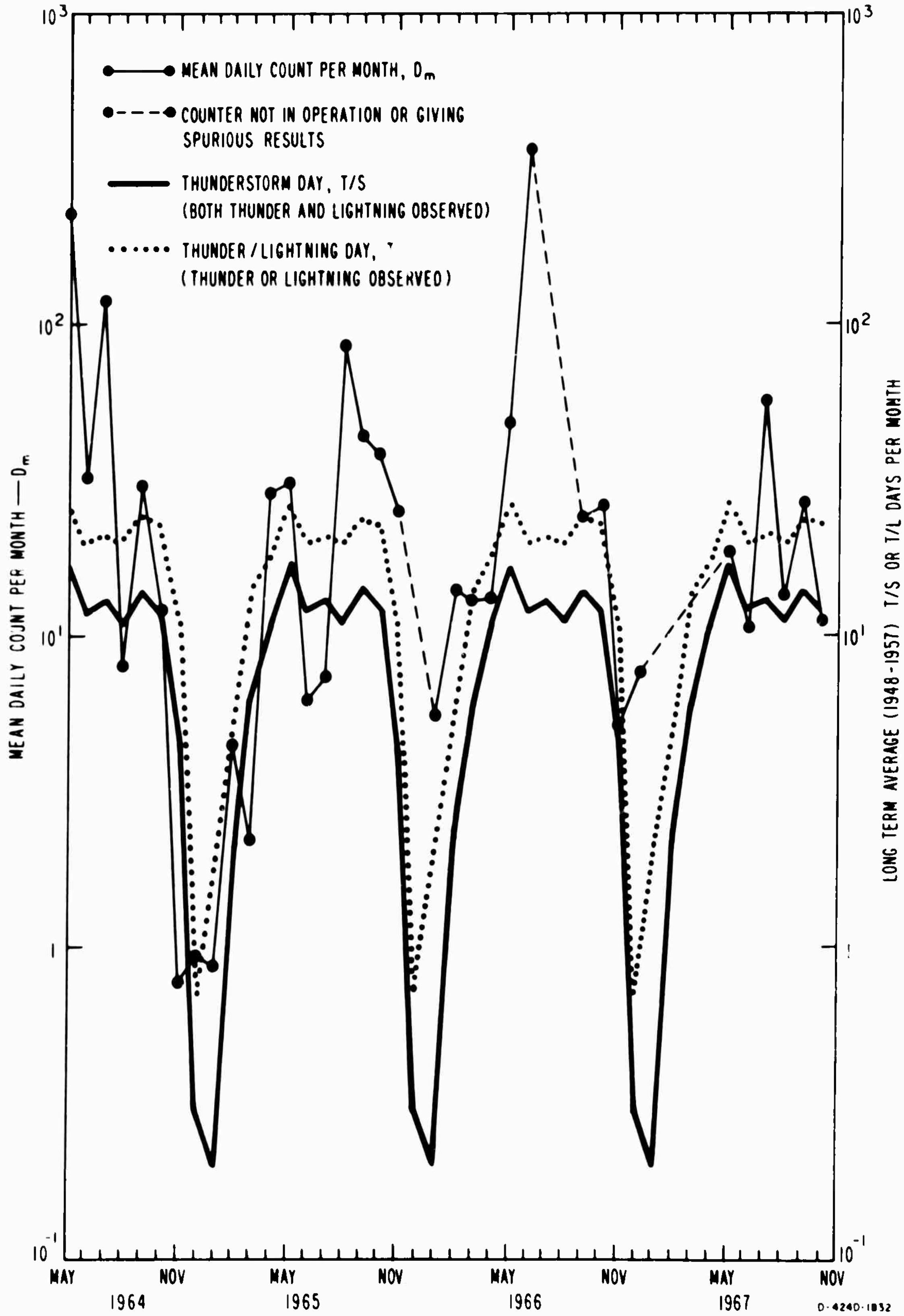

FIG 2 MONTHLY DATA FOR THE BANGKOK CCIR FLASH COUNTER

For instance, the values of D_m for the month of June in the years 1964, 1965, 1966, and 1967 are, respectively, 32, 6.2, 360, and 10.4. However, the trends of the three graphs should be similar, and this is indeed the case. It is noteworthy that in the winter months of weak thundery activity D_m does not drop proportionately as low as does T_m. There are two probable reasons for this behavior. Firstly, as is shown in the analysis of Appendix A, very large impulses from distant storms, which pass unnoticed by local observers, will operate the counter. In addition to this low-level genuine natural background, there will also be occasional spurious pulses of local origin that cause the counter to function. Both these influences will combine to give a small number of counts in winter. It is interesting to note incidentally that Fig. 2 suggests the winter background has increased between 1964 and 1967; this result is quite consistent with an increased incidence of spurious pulses due to the considerable commercial development that has occurred in these years near the counter site.

Figure 2 compares the results for D_m with the long-term average information on T_m. A better interrelationship is to be anticipated if the comparison is made with values of T_m for the actual months of the D_m data. Accordingly, monthly values for T_m were obtained from the Thai Meteorological Department for each of the major reporting stations--nine in all--within 150 km of Bangkok. An average monthly figure for T_m was then derived from the nine individual values for each month. This parameter should be reasonably representative of the general thundery activity in the Bangkok area; it is plotted against D_m in Fig. 3 for the months within the recording period for which both counter and thunderstorm-day data are available.

Figure 3 shows that there is a general relationship between D_m and T_m. This is roughly expressed by the two straight lines of Fig. 3, which have the equations

$$D_m = 2T_m \quad \text{for} \quad T_m \le 3 \tag{4a}$$

$$D_m = (2/3)T_m^2 \quad \text{for} \quad T_m \ge 3 \quad . \tag{4b}$$

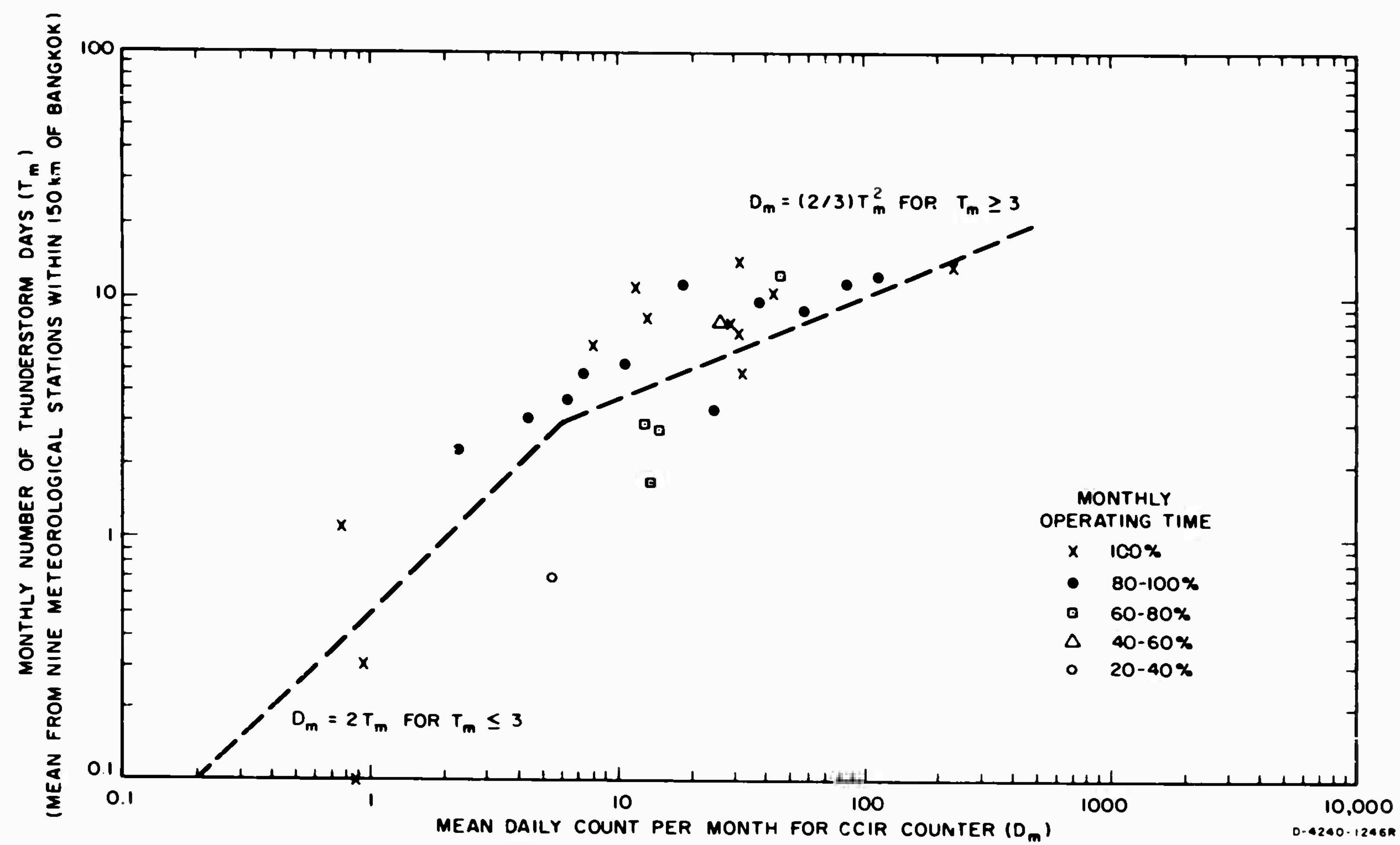

FIG. 3 CORRELATION OF BANGKOK LIGHTNING-FLASH COUNTS WITH METEOROLOGICAL STATISTICS

Equation (4) indicates that the more generally thundery a particular location (e.g., the Tropics), the more intense the activity for any day on which any thunder and lightning is reported as occurring (thunderstorm day). Climatology suggests that this may well be so because of multiple storm occurrences on the same day, increased storm durations, more widespread activity, etc.

It is most interesting that the data of Horner,[24] who used CCIR-type counters at Slough, England, and Singapore, also fits a law similar to Eq. (4 quite well. Horner's results are expressed in terms of M_m, the total number of counts per month; we have $M_m \approx D_m \times 30$. The two straight lines fitting Horner's data approximately are given by

$$M_m = 300T_m \quad \text{for} \quad T_m \leq 3 \tag{5a}$$

$$M_m = 100T_m^2 \quad \text{for} \quad T_m \geq 3 \quad . \tag{5b}$$

Incidentally, for the ERA-type counter some authors[27] consider that the number of counts is proportional to T_m^2, and others[28] that the proportionality is to T_m. It may well be that for the ERA counter--as is apparently the case for the CCIR instrument--the law obeyed depends on the actual value of T_m.

In his work Horner employed a counter with a 3-V threshold and a 7-m antenna, and therefore an effective range R estimated at 30 km. Horner considers that the counts for two CCIR instruments at different sensitivities (whether achieved by changing antennas or threshold voltage settings) should be proportional to the squares of the corresponding effective ranges. Remembering that $M_m \sim 30D_m$, we may combine Eqs. (4) and (5) to give

$$\begin{aligned} M_m &= 3k_1R^2T_m \quad \text{for} \quad T_m \leq 3 \\ M_m &= k_1R^2T_m^2 \quad \text{for} \quad T_m \geq 3 \quad . \end{aligned} \tag{6}$$

From Eqs. (5) and (6), with R = 30 km we have $K_1 \approx 0.11$. From Eqs. (4) and (6) with R = 11 km, we have $K_1 \approx 0.17$. Thus the general empirical law

$$\begin{aligned} M_m &\approx 30D_m \approx 3 \times (0.14)R^2T_m \quad \text{for} \quad T_m \leq 3 \\ M_m &\approx 30D_m \approx 0.14R^2T_m^2 \quad \text{for} \quad T_m \geq 3 \end{aligned} \tag{7}$$

is a reasonable fit to the CCIR counter data at Slough, Singapore, and Bangkok.

Relation (7) when combined with the long-term thunderstorm-day statistics for Bangkok suggests that some 60 discharges occur per km^2 per annum, with April to October being the active season. Perhaps some 15% of these flashes are to earth (Appendix B).

B. Daily Counts

The distribution of daily counts, D_c, is given in Fig. 4. This distribution is approximately log-normal over the lower range of count values but diverges at the upper extreme. Such behavior is to be anticipated because the influence of local storms makes the large-count-value end of the distribution unusual. The deviations from a log-normal distribution are illustrated in Fig. 5, in which the daily count statistics are plotted on probability paper. The counts are expressed in decibels relative to the median value ${}_mD_c$--that is, as $20 \log_{10} D_c/{}_mD_c$. The value of ${}_mD_c$ is about 4. A log-normal distribution on the plot of Fig. 5 would be a straight line.

Horner[10] has estimated that when using a counter with a 7-m antenna and a 3-V threshold, the total of counts will exceed one hundred for any day on which local thunder occurs. This is for R = 30 km. Assuming uniform thundery activity, with the Bangkok counter (R = 11 km), a thunderstorm day should correspond to a daily count of more than about 13 = $[100 \times (11^2/30^2)]$. About 29% of the days actually had counts exceeding 13; in a year this would represent 106 thunderstorm days. The long-term

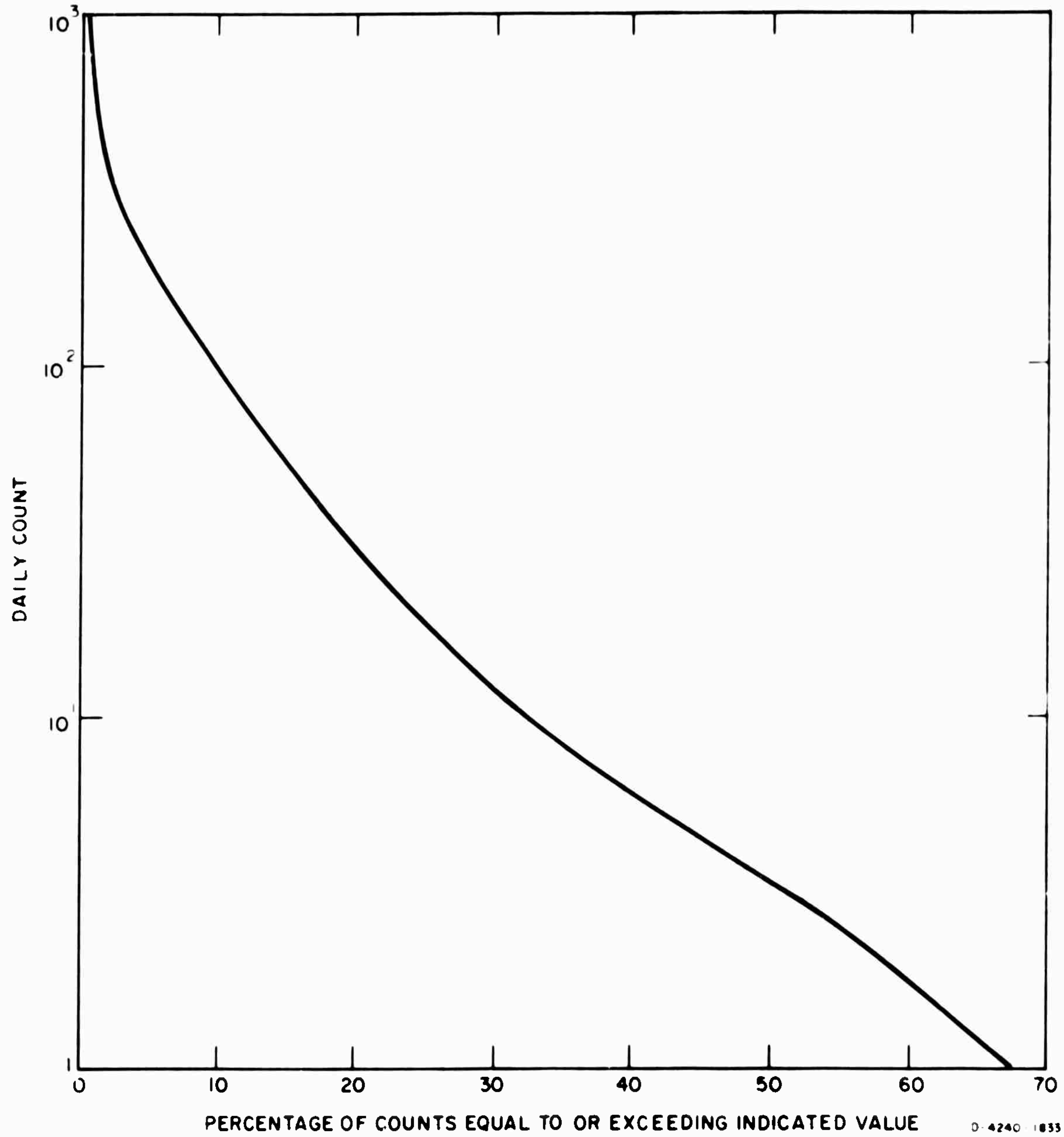

FIG 4 DISTRIBUTION OF DAILY COUNTS FOR BANGKOK CCIR FLASH COUNTER

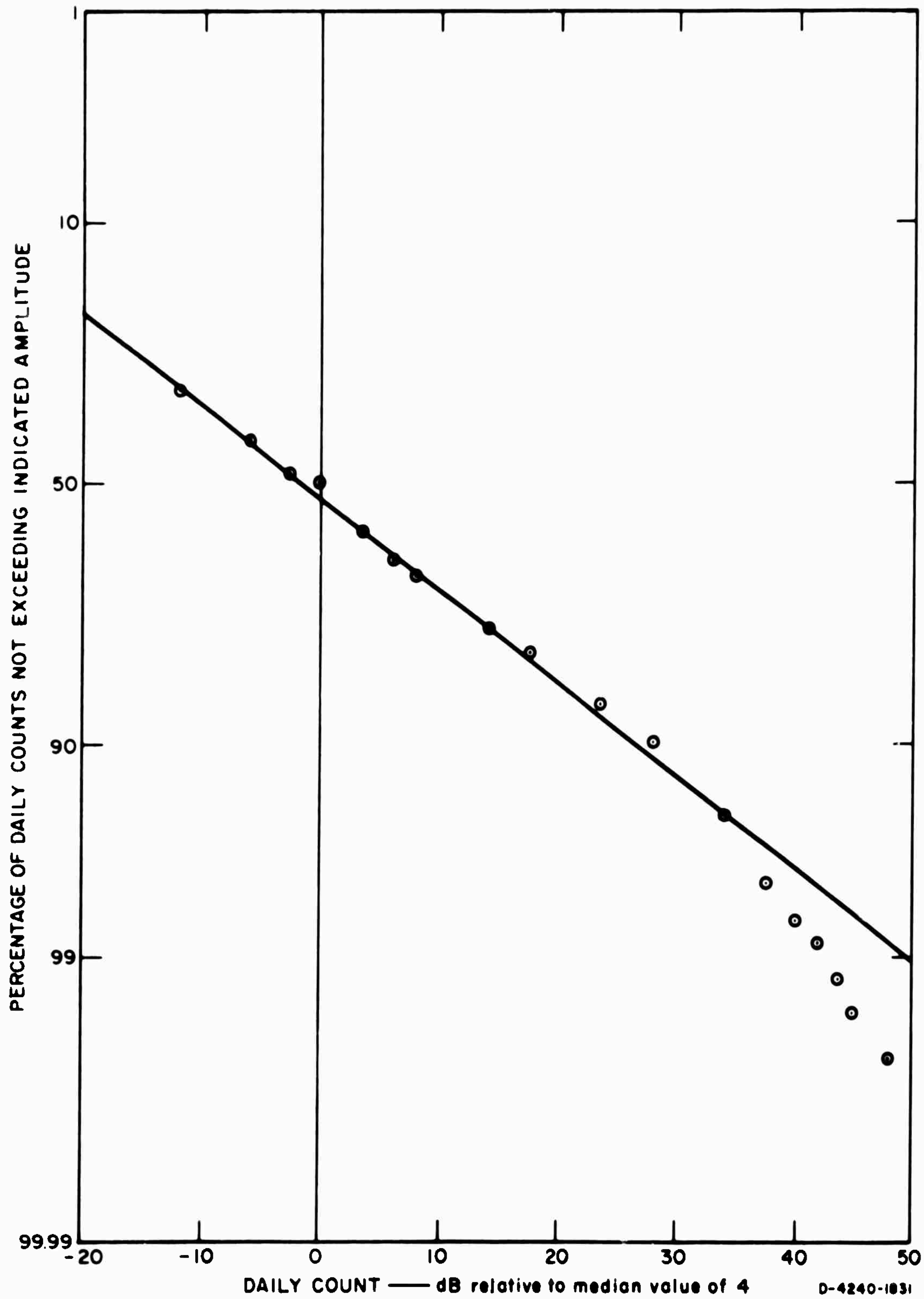

FIG. 5 DISTRIBUTION OF DAILY COUNTS SHOWING DEVIATION FROM LOG-NORMAL LAW

average number of thunderstorm days per annum for Bangkok as determined from meteorological observations is 103; the agreement is remarkable.

Very large values of D_c were fairly rare but they accounted for a high proportion of the total number of flashes counted. For example, counts exceeding a hundred were registered on only 10% of days, but these days were responsible for over half of the total counts in the long-term period.

Horner[10] estimates as an approximate empirical rule that, for a given day, D_c is approximately three times the maximum count per hour registered on that day. On days of intense thunderstorm activity at Slough, England, typical values of maximum hourly count and of D_c are respectively 200 and 600; however, one very exceptional day (September 5, 1958) yielded counts an order of magnitude larger for both parameters. At Singapore, a very thundery day gives $D_c \approx 2,000$ and a maximum hourly count of some 600.

The results in the above paragraph are for a counter with an effective range, R, of 30 km. Scaling down the Singapore results to the Bangkok situation ($R \approx 11$ km) we would expect a day of very marked thundery activity to give a D_c value of about 250 to 300. Figure 4 indicates that some 3% of all days have $D_c \geq 250\text{-}300$. This would imply that of the approximately 100 thunderstorm days recorded per annum at Bangkok, about ten have really violent activity; meteorological records and general experience suggest that this estimate is not unreasonable.

Incidentally, the peak value of D_c ever recorded on the Bangkok counter was 1278.

C. Diurnal Variation

A limited amount of information on the variation of thundery activity as a function of time of day is available from the Bangkok counter results. This is because from May 1965 onward, counter readings were obtained four times a day for the time blocks (local time) of 2400-0600, 0600-1200, 1200-1800, and 1800-2400 hours. Some results are presented in Fig. 6. In order to identify trends these have been smoothed by the use of three-month running means.

Figure 6 generally confirms the tendencies already noted from less extensive data.[6] In the early months of the year the peak activity is between 0600 and 1200; in spring the peak moves to 1200-1800, and during late summer and fall to 1800-2400. Activity in the 2400-0600 block is relatively low except during autumn and winter. These trends have some consistencies with meteorological information (Appendix D); for instance, heat thunderstorms are especially common in April and May, and this agrees with the observed maximum of activity being in the local afternoon. Figure 7 presents the same information as that given in Fig. 6, but the abscissal scales have been arranged so as to demonstrate the general parallelism of the annual trend (suitably phased) for each time block.

Figure 8 presents three-month running means of the actual counts for the four time blocks. This plot emphasizes the generally low activity during some parts of the year; this point is not indicated by the graphs of Figs. 6 and 7. If the absence (or presence) of thunderstorms is vital for some operation, then the most favorable time for operation can be estimated from Fig. 7. Assuming that thunderstorms are undesirable, Fig. 8 shows that during the summer (April-August) the afternoon and early night hours (1200-2400) should be avoided, while in winter (December-February) it is the opposing time period (2400-1200) that should be shunned: however, the relative activity indicated in Fig. 8 shows that the former constraint is much more significant than the latter.

The information on the precise way in which tropical lightning activity varies with time of day and season is scanty. The most detailed data is that of Horner[24] for Singapore; this is shown on Figs. 9 and 10. At Singapore there is a surprising concentration of diurnal activity within the time block 1200-1800 LMT; this is so at all times of the year. Aiya[17] finds that at Poona (19^oN, 74^oE) and Bangalore (13^oN, 77^oE) the peak local activity during the thundery seasons usually occurs between 1400 and 0400 LMT, while the activity begins to build up shortly before midday.

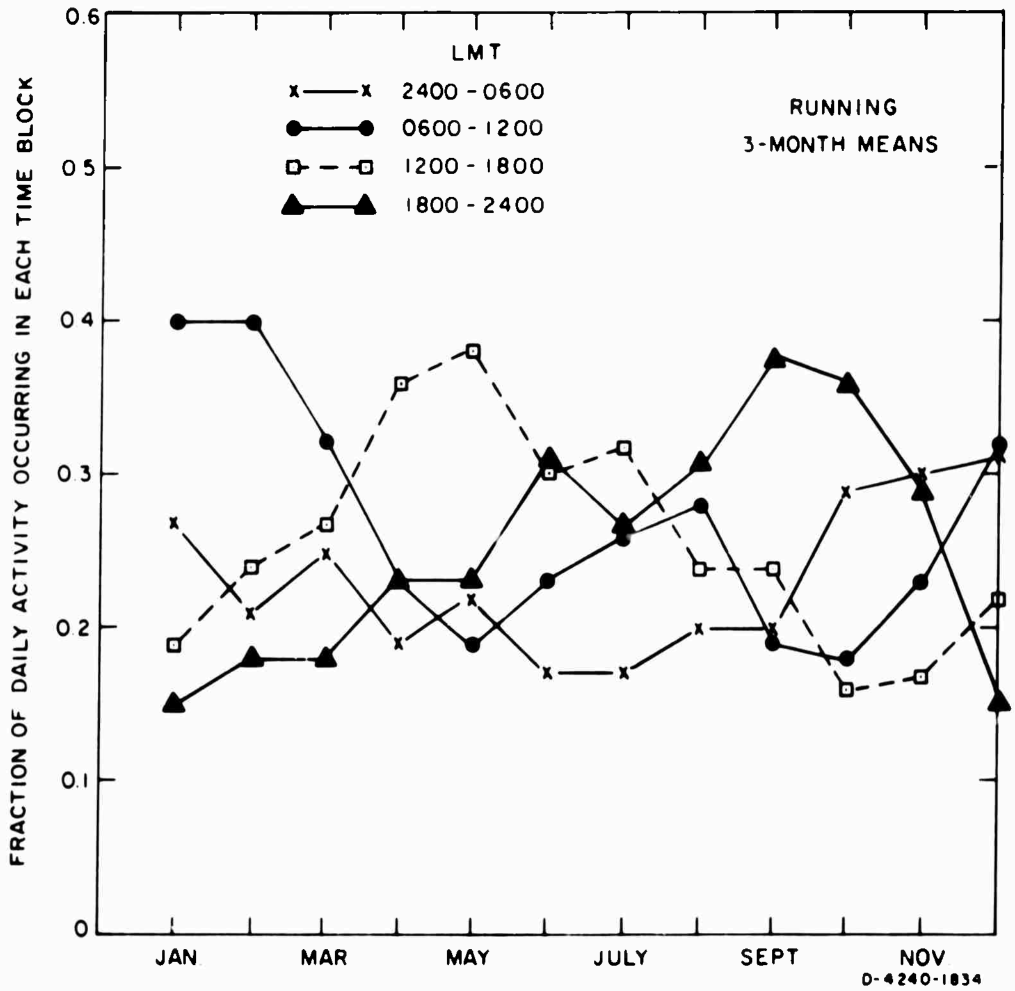

FIG. 6 DIURNAL LIGHTNING-FLASH ACTIVITY AT BANGKOK

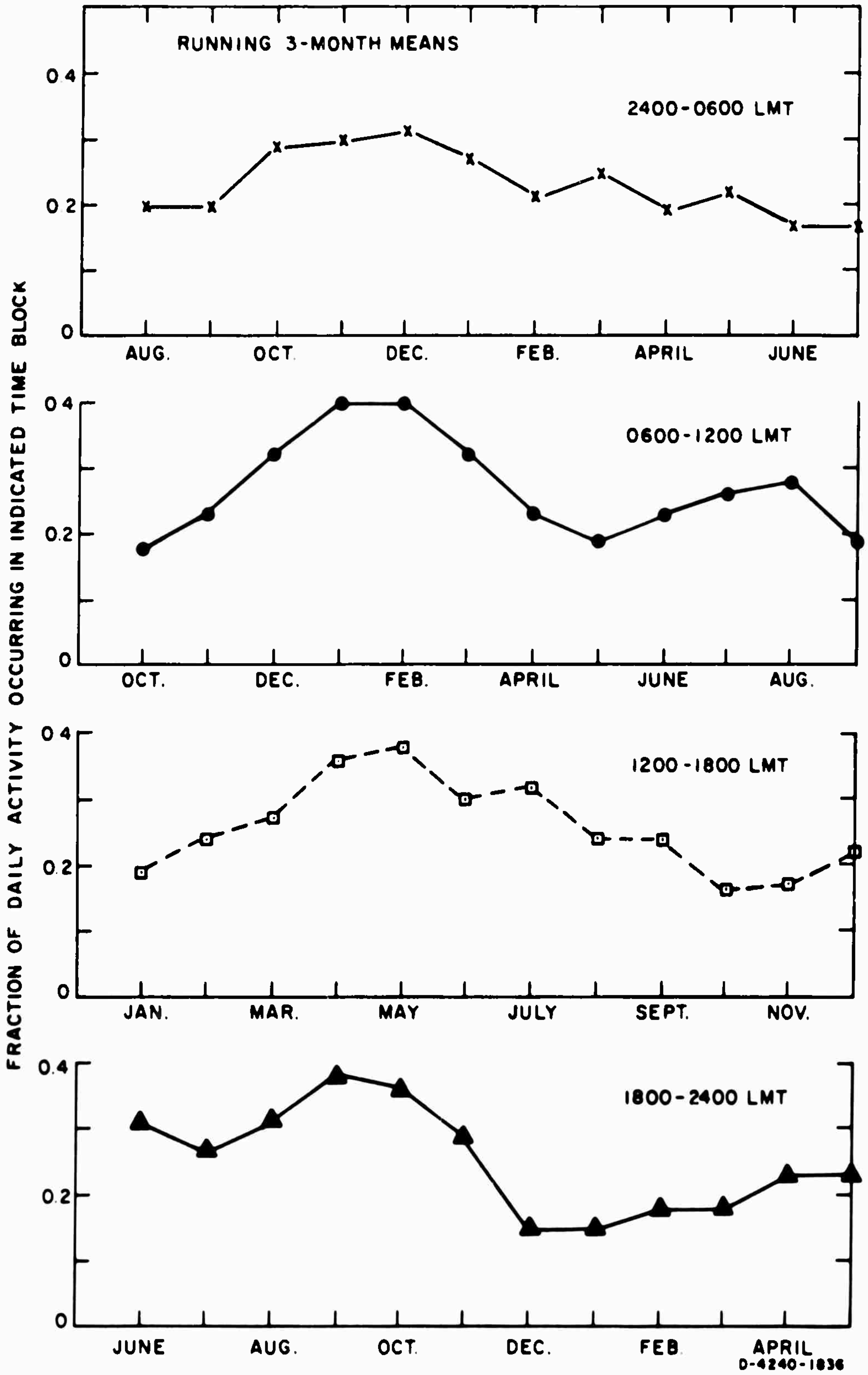

FIG. 7 SEASONAL TREND OF DIURNAL LIGHTNING-FLASH ACTIVITY AT BANGKOK

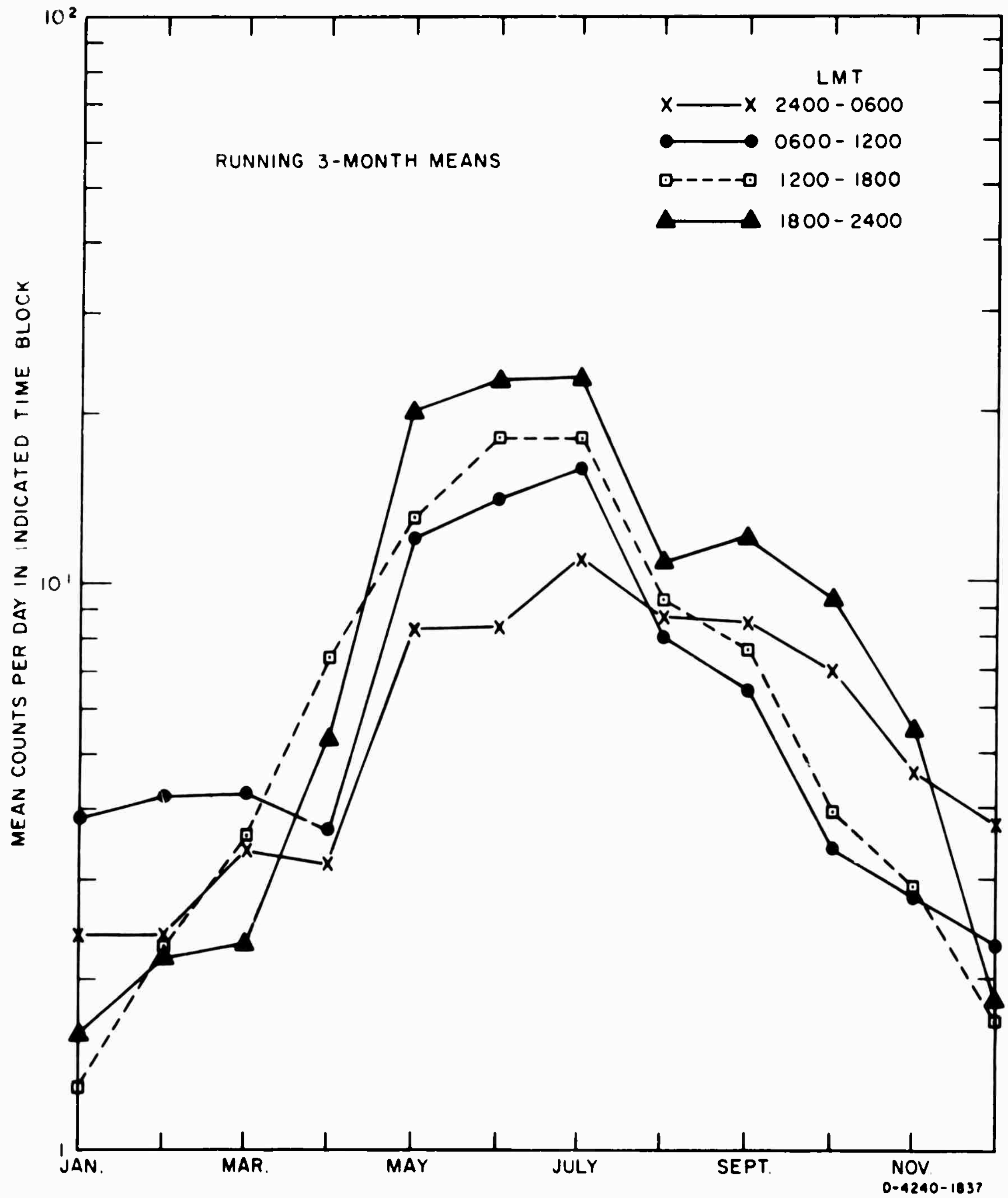

FIG. 8 MONTHLY CHANGE IN LIGHTNING-FLASH COUNTS FOR FOUR DAILY TIME BLOCKS

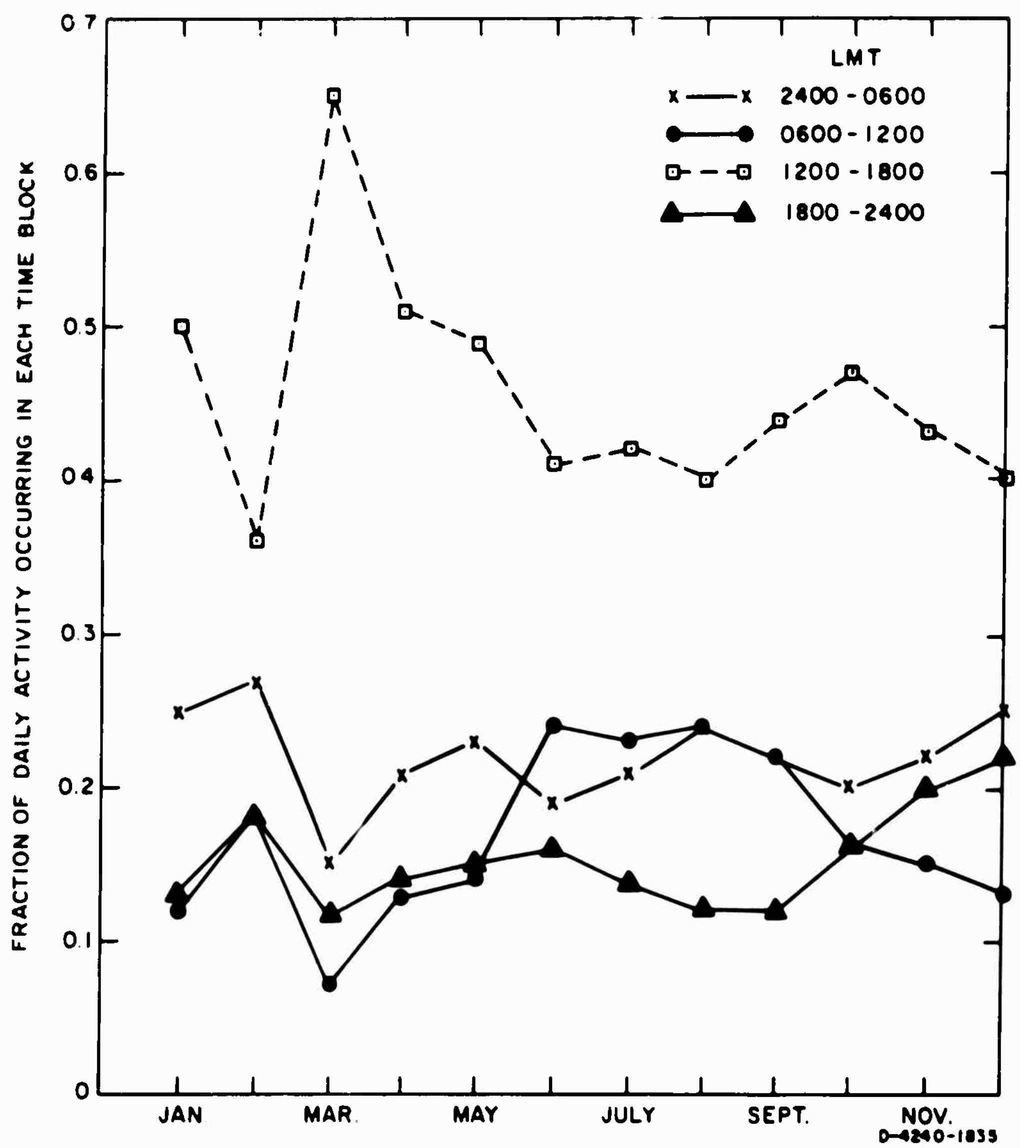

FIG. 9 DIURNAL LIGHTNING-FLASH ACTIVITY AT SINGAPORE

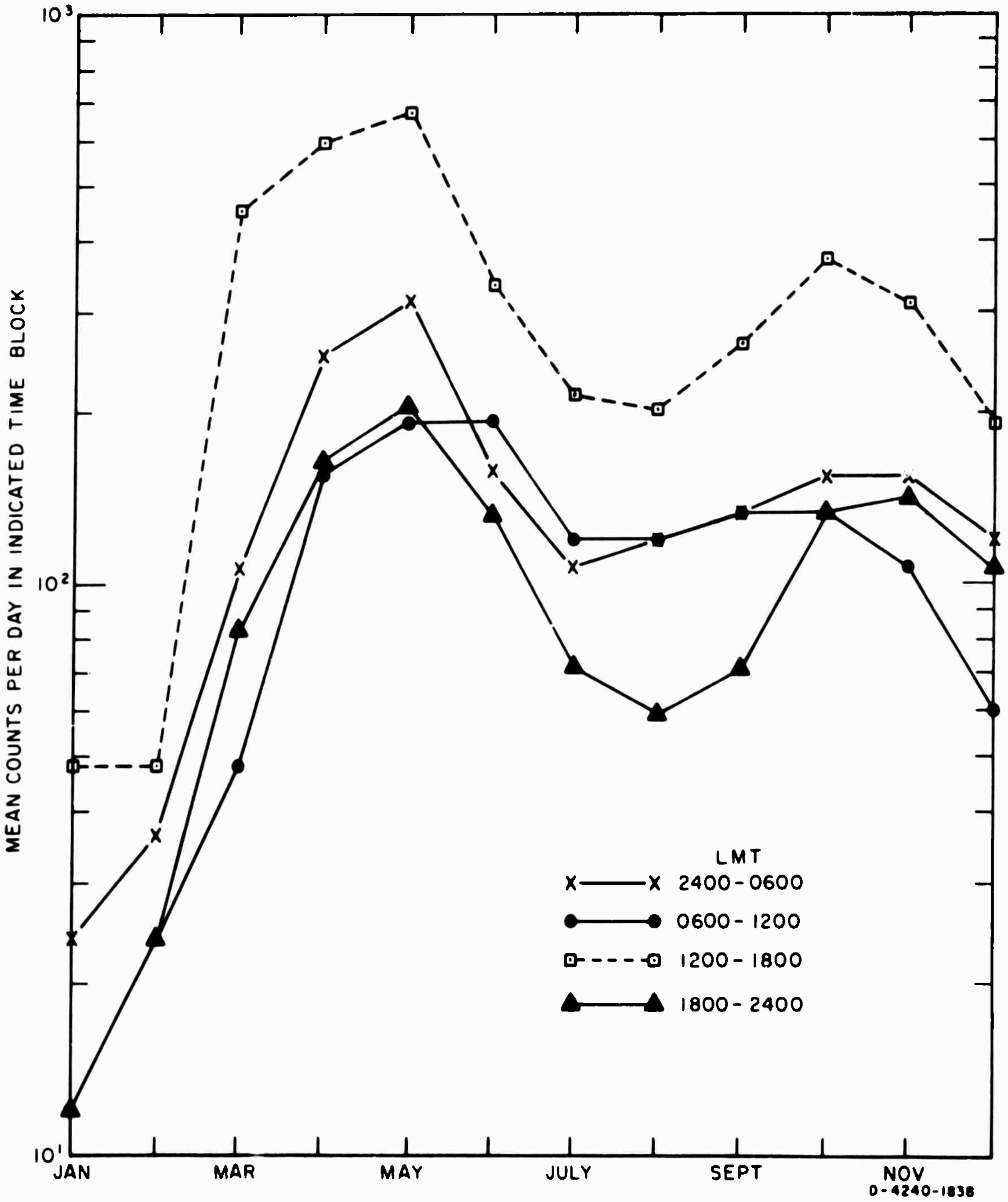

FIG. 10 MONTHLY CHANGE AT SINGAPORE IN LIGHTNING-FLASH COUNTS FOR FOUR DAILY TIME BLOCKS

These Indian results are reasonably consistent with the data for Bangkok represented in Fig. 6. It may well be that the very regular behavior throughout the year at Singapore is not really representative of that for a land station in the tropics. Singapore is somewhat unusual in that its situation--almost exactly on the equator, and largely surrounded by sea--produces a climate that in several respects changes little, seasonally.

Figure 10 may be compared with Fig. 8. From Fig. 10, two periods of strong thunderstorm activity are readily identified at Singapore. These periods are the main maximum (April-May) and the subsidiary peak (September-November) later in the year; they coincide approximately with the immediately post-equinoctial months. For Bangkok (Fig. 8) there is one pronounced maximum (May-July), but only a very slight indication of any later intensification in activity (September-October).

The differences in the monthly trends shown in Figs. 8 and 10 for Bangkok and Singapore, respectively, are generally consistent with meteorological information, and the seasonal variation of solar zenith angle at the two stations. Note that the ordinate scale for Fig. 10 is ten times that for Fig. 8, and the ratio of counts--Singapore to Bangkok--is greater still. One reason for the differences in counts is that (as discussed in Sec. III-A) the Singapore counter was about $7.5 \approx [(30/11)^2]$ times as sensitive as the Bangkok instrument. A second reason is that Singapore with 171 thunderstorm days per annum is in a more electrically active area than Bangkok (103 thunderstorm days per annum). Since, for tropical stations of high thundery activity the number of counts is proportional to the square of the number of thunderstorm days [Eq. (7)], when using identical instruments the counts at Singapore should be greater than the counts at Bangkok by a factor of about 2.75 $[(171/103)^2]$. Combining the two factors (7.5×2.75) leads to a ratio of about 20 between the counts at Singapore and at Bangkok; this is approximately that indicated by Figs. 8 and 10.

IV LIGHTNING-FLASH-COUNTER DATA OBTAINED AT LAEM CHABANG

The low-noise station at Laem Chabang has been adequately described in other Special Technical Reports.[2,8,29] Lightning-flash-counting equipment was operated at this site in order to provide information supplementary to the radio noise data being obtained simultaneously at Laem Chabang. Two counter installations were employed. These were a transistorized version of the ERA Counter* supplied on loan through the kindness of Professor S. A. Prentice, University of Queensland, Brisbane, Australia, and the so-called Lightning-Flash Analyzer.[29]

A. Results With the Prentice (ERA) Counter

The design of this counter is due to Barham.[14] Essentially it is a transistorized version of the Pierce/ERA instrument, which preserves the basic features--notably frequency response and sensitivity-- of its vacuum-tube forerunners. The performance of the Barham circuitry has been thoroughly tested during extensive experiments in Australia under the general direction of Professor S. A. Prentice.

The counter was made available on loan by Professor Prentice. In accordance with his instructions, a standard ERA counter antenna was built at Laem Chabang. This antenna consists of six parallel horizontal wires spaced 15 cm apart and at a height of 5 m. When an ERA counter is fed from the standard antenna, CIGRE practice[25] is to adjust the triggering threshold so that triggering occurs if the field developed at the antenna, within the bandwidth of the counter, exceeds 5 V/m. The test signal in the Barham counter is pre-set to correspond to this standard triggering level. Bunn[26] has estimated that when the ERA counter is employed in the standardized manner, the effective ranges are 30 km for ground flashes and 20 km for cloud discharges (Sec. II-E); these values should apply to the Laem Chabang installation.

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* This will be referred to as the "Prentice (ERA)" counter.

Unfortunately the Prentice (ERA) counter was not set up at Laem Chabang until October 1967. Thus data were obtained only for a few months. The data sample was far too limited for any significant conclusions to be derived regarding temporal variations such as seasonal or diurnal effects. However, the measurements showed conclusively that the counter was a simple and reliable indicator of local thunderstorm activity.

A typical example of the counter data is shown in Fig. 11. This gives the counts over half-hour periods for four days--October 14-17, 1967--of intermittent thundery activity. The distribution of the half-hour counts illustrates the effectiveness of the Prentice (ERA) counter as an "on-off" indicator of local storms; there are many instances of zero counts interspersed among the high-count periods. This decisiveness in operation is of course to be anticipated from the theoretical indication (Fig. 1) that, because of the inverse cube law of signal variation with distance, the effective range of ERA-type counters is fairly precisely defined.

Figure 12 shows the distribution of daily counts, D_c, obtained with the Prentice (ERA) counter at Laem Chabang for the last three months of 1967. It may be compared with Fig. 4. This comparison illustrates convincingly that the ERA design of counter is a more effective and reliable indicator of thundery activity occurring in the vicinity of a recording station than is the CCIR instrument. The data suggests that some interesting oscillations are superimposed upon the smooth curve of Fig. 12. These oscillations may be real and bear some relation to the distance of the thundery activity; however, the data sample is insufficiently large for this point to be clarified at present.

A major objective of the work in Thailand was to establish the effect of a local thunderstorm upon noise power. Most of the information in this connection is presented in Special Technical Reports 37 and 47. However, Fig. 13 shows the correlation between noise power at 0.53 MHz received on a vertical antenna, and the Prentice counter results; in this figure, corresponding values of noise power (referred in dB to an arbitrary reference level) and counts are plotted for hourly periods covering the four days October 14 to October 17. It is apparent that the presence of local

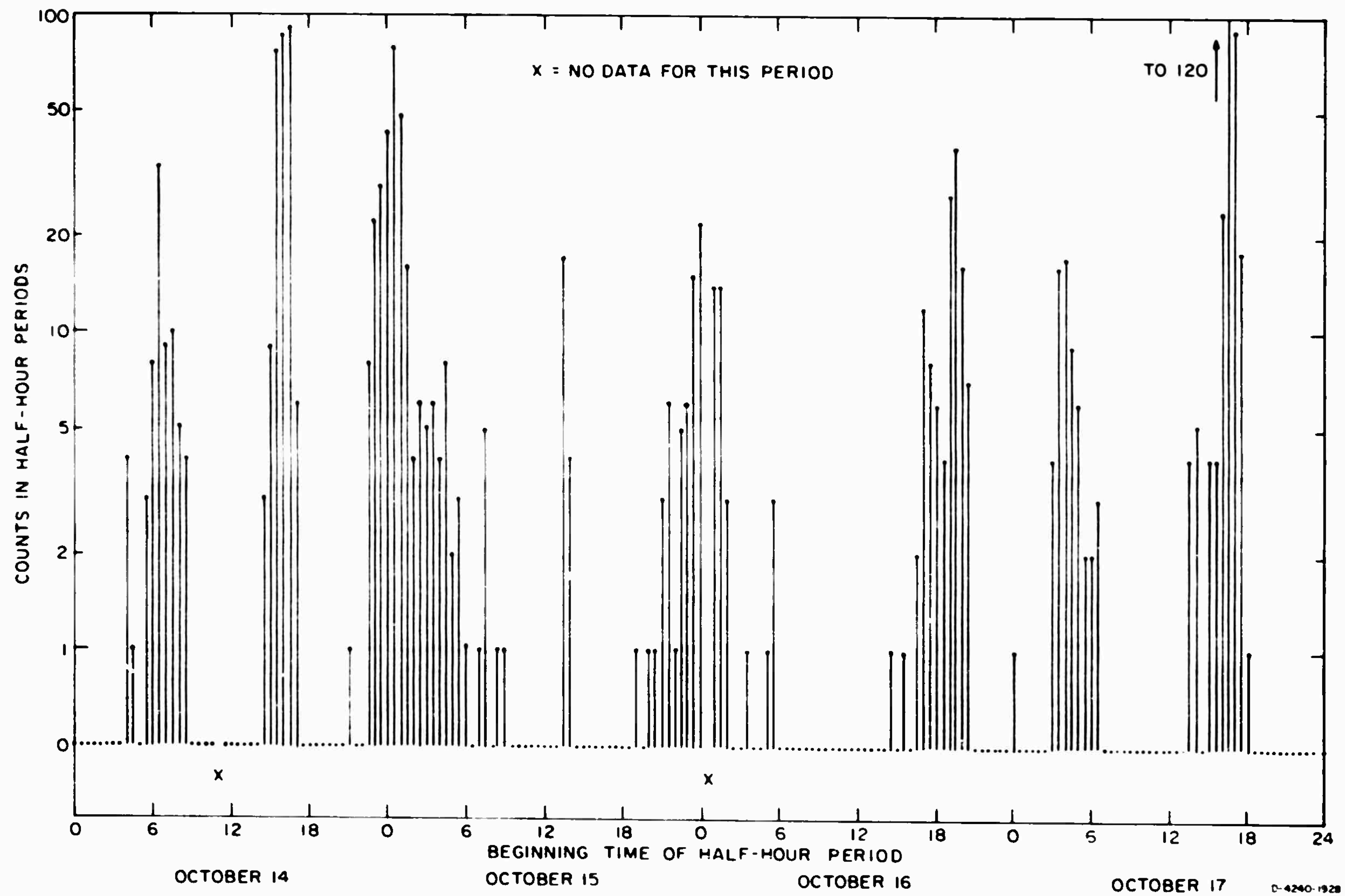

FIG. 11 PERFORMANCE OF PRENTICE ERA COUNTER, LAEM CHABANG, OCTOBER 14-17, 1967

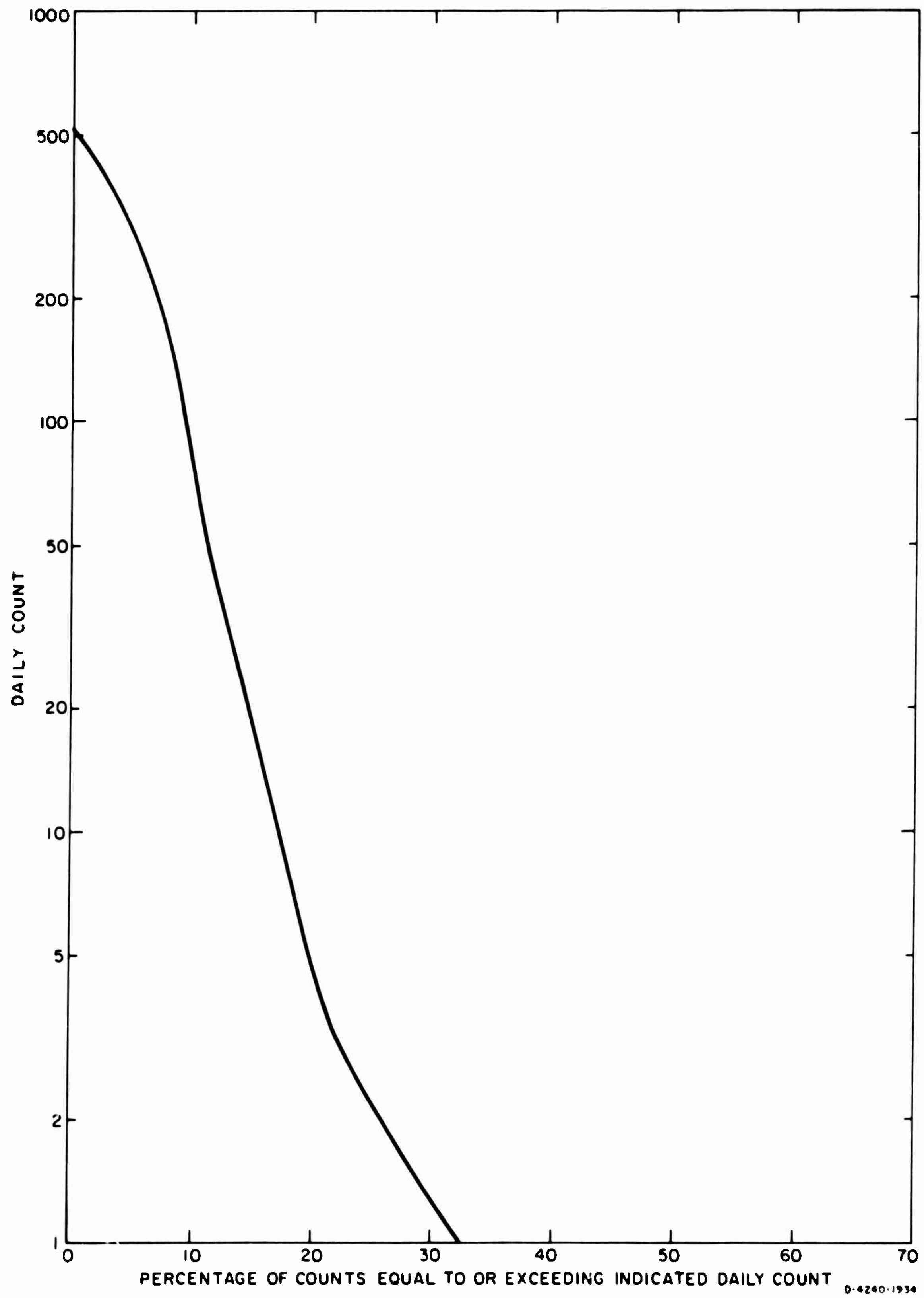

FIG. 12 DISTRIBUTION OF DAILY COUNTS FOR PRENTICE ERA COUNTER AT LAEM CHABANG

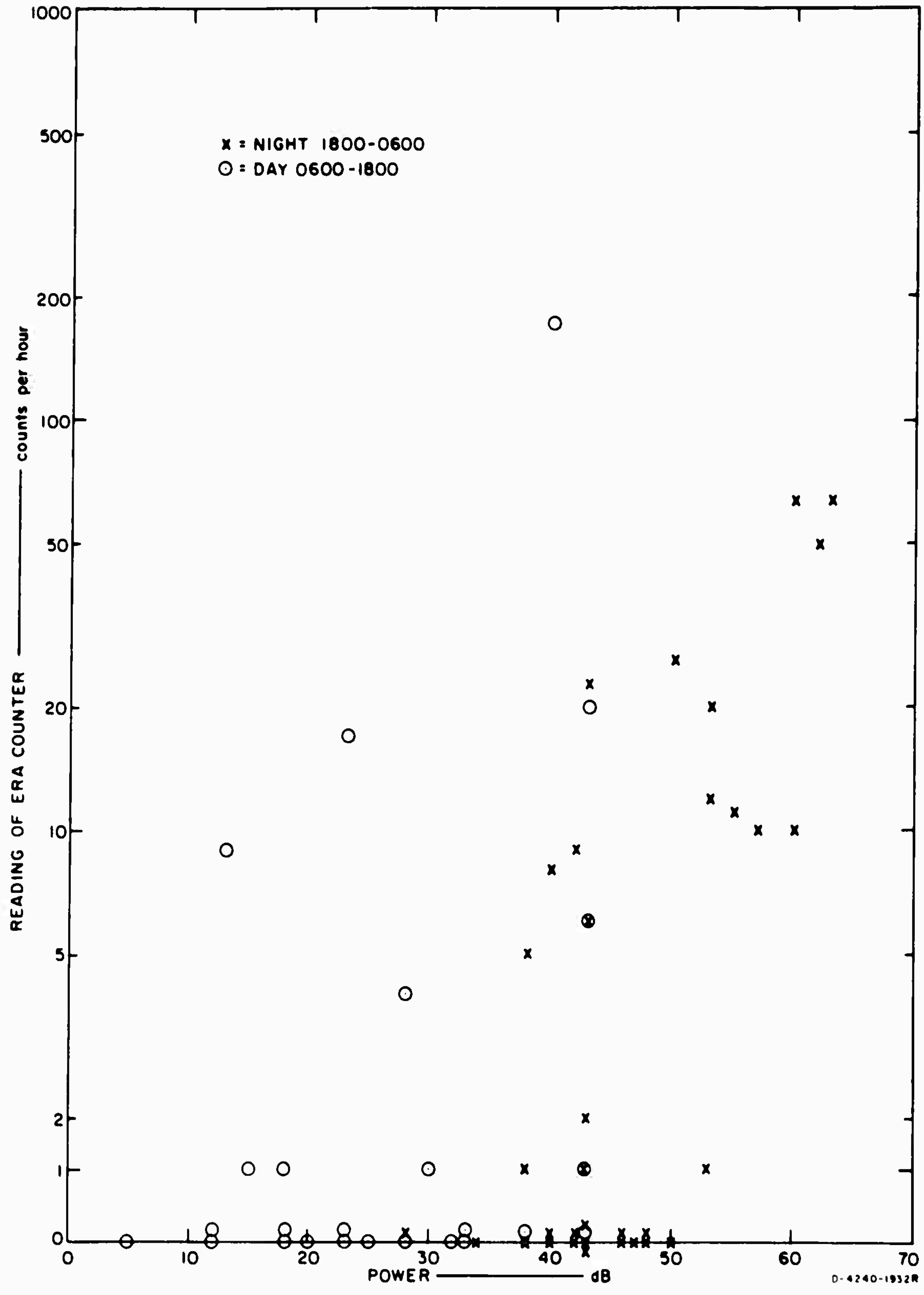

FIG. 13 RELATIONSHIP BETWEEN PRENTICE ERA COUNTER READINGS AND NOISE POWER AT 0.53 MHz

thundery activity, as shown by the Prentice (ERA) counter, increases the power of the received atmospheric noise at 0.53 MHz by some 10 to 20 dB.

B. Results with the Lightning-Flash Analyzer

1. General

This installation has been described in a Special Technical Report.[29] The original intention was to design, construct, and operate a fairly elaborate arrangement for counting lightning flashes at the Laem Chabang low-noise site. The equipment as built included two sections with frequency passbands corresponding approximately to those of the ERA and CCIR instruments; each section had three sensitivities feeding separate registers, the readings of which were obtained at half-hour intervals. The two sections functioned via a common antenna.

Unfortunately a modification of the antenna circuit was made by the insertion of a 20-kΩ resistor. The effect of this change is discussed in detail in Appendix C.

Briefly the result was to move the overall system response into the VLF and LF bands (3 to 300 kHz). While the effect of this alteration upon the counter with nominal CCIR characteristics was not too serious, it was disastrous as regards the ERA-type counter; in fact this counter was essentially converted into one somewhat similar in frequency response to a CCIR instrument but with a much reduced sensitivity.

Summarizing, the six sets of data from the Laem Chabang lightning-flash analyzer should represent data from two lightning-flash counters with effective frequency passbands in the VLF and LF region. The effective passbands for the two counters are not very different, nor are they far removed from the nominal passband for a CCIR-type counter; the difference is in a bias--as compared with the CCIR instrument--toward higher frequencies. Thus the six sets of data should approximate that from a CCIR-type counter having six sensitivity settings.

Horner[24] has shown that to a first approximation the effective range of a CCIR counter is inversely proportional to V_T. This implies that when long-term averaging is carried out over many thundery situations the number of counts obtained with counters of different sensitivities should vary as $(V_T)^{-2}$; alternatively, a comparison of the actual counts indicates the relative sensitivities.

Table I shows the results obtained for the relative sensitivities both from theory (Appendix C) and the actual count data. The quantity k is included to represent the factor by which the ERA circuitry is diminished in sensitivity as compared with the CCIR channels (see Figs. C-5 and C-6) Over the first three months of analyzer operation (Sept.-Nov. 1966) the last column of Table I shows that the relative sensitivities derived from the data agreed fairly well with the theoretical anticipations. The three ERA channels all yielded a consistent value of k--about 5×10^{-2}; this represents about 25 dB down from the corresponding CCIR channels, and is therefore in reasonable agreement with the curves of Figs. C-5 and C-6.

Table I

RELATIVE SENSITIVITIES OF CHANNELS IN LAEM CHABANG LIGHTNING-FLASH ANALYZER

Channel	Trigger Voltage, V_T (volts)	Theoretical Expectation	Deduced from Actual Counts Sept 1966-Oct 1967	Deduced from Actual Counts Sept-Nov 1966
CCIR-1*	1	1	1	1
CCIR-3	3	11×10^{-2}	7×10^{-2}	18×10^{-2}
CCIR-10	10	10^{-2}	5×10^{-3}	5×10^{-3}
ERA-1	1	k	4×10^{-2}	3×10^{-2}
			(Hence $k \approx 4 \times 10^{-2}$)	(Hence $k \approx 3 \times 10^{-2}$)
ERA-3	3	$k(11 \times 10^{-2})$	2×10^{-2}	5×10^{-3}
			(Hence $k \approx 2 \times 10^{-1}$)	(Hence $k \approx 5 \times 10^{-2}$)
ERA-10	10	$k(10^{-2})$	6×10^{-3}	6×10^{-4}
			(Hence $k \approx 6 \times 10^{-1}$)	(Hence $k \approx 6 \times 10^{-2}$)

* The number following the hyphen is the Trigger Threshold, in Volts.

However, when all the data (Sept. 1966 through Oct. 1967) are considered, the results from the six channels of the Lightning-Flash Analyzer become quite lacking in internal consistency. One aspect of this behavior is the wildly different estimates obtained for k (Table I, Column 4). Another peculiar feature was a systematic fall with time in the sensitivities of CCIR-3 and CCIR-10 channels relative to CCIR-1; in September and October 1967, for instance, these sensitivities had decreased to 5×10^{-3} and 2×10^{-4} respectively. The ERA channels--always comparatively insensitive--behaved capriciously over the entire data period, and the results from these channels did not correlate either with each other or with the CCIR-1 data. The most disturbing overall aspect, however, of the data, from the five channels other than CCIR-1, was that their counts--although usually small in number and therefore presumably originating in close storms--bore no relation to the incidence of local thunderstorms as indicated by meteorological reports.

It is difficult to avoid the conclusion that over the recording period most of the counts on channels CCIR-3, CCIR-10, and the three ERA channels, were spurious and not due to lightning. The triggering pulses may have been generated by adjacent equipment or internally within the Lightning-Flash Analyzer. In any case it is almost impossible to distinguish between the genuine and the false counts, and it is probably profitless to even attempt to do so. Accordingly, the only Laem Chabang Analyzer results that will be discussed are those from the CCIR-1 channel.

2. The CCIR-1 Channel

It is believed for several reasons that most of the counts on this channel were genuine and that the data can be taken as truly representing the incidence of lightning activity. Some of these reasons are as follows:

(1) The hourly count rates varied considerably--typically from 2 or 3 to over 500. This whole range in variation might be covered within perhaps a week with no obvious preference for any particular counting rate. Such behavior would not be expected if the interference background was appreciable.

(2) The counting rates were often large, usually exceeding 30 per hour. It seems likely that operators would have recognized the existence of any interfering source that gave such high triggering rates.

(3) The results compare reasonably well with those obtained for the Bangkok CCIR Counter (Sec. III), for the available comparison months (Sept.-Dec., 1966; May-Oct., 1967). Over the entire comparison period Laem Chabang CCIR-1 registered approximately 130 times as many counts as did the Bangkok instrument; comparisons for the individual months* did not deviate unreasonably from this average value of 130, and did not indicate any temporal trend.

(4) If the effective range of the Bangkok Counter is 11 km, (Sec. III) then with a count ratio of 130, the effective range of CCIR-1 should be 125 km ($11\sqrt{130}$). Alternatively we may estimate the ratio of effective ranges for the CCIR-1 and the Bangkok-CCIR counters from the nominal respective values for V_T and antenna length. At Bangkok we have $V_T = 6$ V and an antenna length of 5 m, while for CCIR-1, $V_T = 1$ V and the antenna length is 6.6 m. Thus the range ratio should be about 8 ($6 \times 6.6/5$); this is in fair agreement with 11.5 ($\sqrt{130}$).

(5) The CCIR-1 data show quite good correlation with the incidence of local thunderstorms. Item 4 above indicates that the effective range for CCIR-1 is of the order of 100 km. Accordingly, Table II was prepared, showing for November 1966 the mean hourly count per day, with days for which thunderstorms were reported by meteorological stations within 150 km of Laem Chabang separated from days of no local thundery activity. Obviously the count distributions for the two categories of days are entirely different.

Even though the CCIR-1 information can be accepted as genuine, its utility is limited. The results are derived from a counter of a single fixed sensitivity setting, and the data period (Sept. 1966-Oct. 1967) is fairly short. For the latter reason in particular, conclusions regarding seasonal, monthly, and daily counts are best derived from the Bangkok long-term record (Sec. III). The limited supplemental information that the CCIR-1 data provide generally confirms and nowhere seriously contradicts the findings of Sec. III.

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* With the exception of August 1967.

Table II

RELATION BETWEEN COUNTS AND INCIDENCE OF LOCAL THUNDERSTORMS
(CCIR-1, Laem Chabang, November 1966)

Mean hourly count values per day (No record available for November 16)	
Days on Which Thunderstorms Were Reported Within 150 km	Days on Which no Thundery Activity Occurred Within 150 km
55	3
73	4
75	17
85	18
117	18
118	22
119	23
147	24
161	29
381	30
581	34
	37
	39
	45
	51
	59
	68
	69

In one respect, however, the CCIR-1 results improve on the Bangkok records. This is because the half-hourly readings obtained with the CCIR-1 recording arrangements enable a better delineation to be made of the dirunal variation. This fine temporal structure in the data also enables other conclusions to be derived. For example, Fig. 14 compares the hourly counts obtained with the CCIR-1 and the Prentice (ERA) counters for the period of Oct. 14-17, 1967, previously considered (Fig. 11). There is a general interrelationship, as is to be anticipated. However,

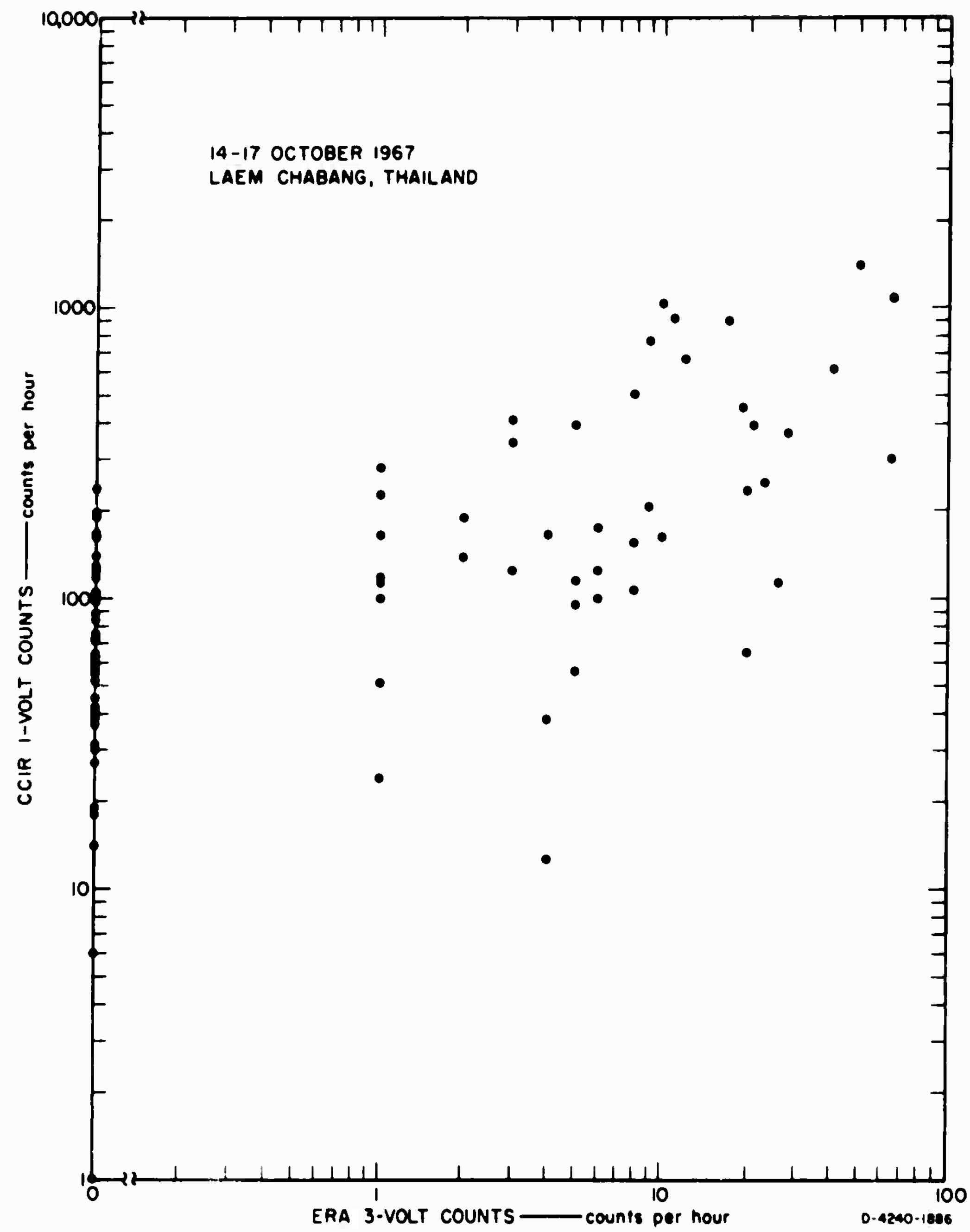


FIG. 14 COMPARISON OF HOURLY COUNTS FOR PRENTICE ERA AND CCIR-1 COUNTERS

the CCIR-1 often indicates appreciable activity when the ERA Counter reading is zero. This confirms the conclusion evident from Figs. 4 and 12, that the ERA instrument is a more definite indicator of local thunderstorms than is the CCIR design. The CCIR circuitry will always have a tendency to respond to the bigger VLF impulses from storms at moderate distances (Fig. A-4). When, as with the CCIR-1 counter, the sensitivity and consequently the effective range (about 100 km) are large, a substantial background of counts will be provided by the highest-amplitude signals from quite distant storms.

The diurnal variation of the CCIR-1 results is shown in Figs. 15, 16, and 17 for each of the fourteen months for which data are available. These figures may be compared with Figs. 6, 7, and 9.

There are of course significant reasons why diurnal variations if obtained with counters of similar design but different sensitivities should not be identical. A counter with low sensitivity and short effective range will have its readings dominated by the influence of local thunderstorms. As the sensitivity, and therefore the effective range, is increased, the proportionate effects of impulses propagating from distant storms will become greater. Since neither the local activity, the distant storms, nor the propagational effects follow identical variational laws with respect to Universal Time, the exact form of diurnal variation must inevitably depend on sensitivity.

The pattern of behavior for a particular month cannot be expected to be reproduced every year. Figure 15 illustrates this point. October 1966 and October 1967 produced quite similar diurnal variations; however, there is a substantial difference between the curves for September 1966 and September 1967. August 1967 yielded an exceptionally small number of counts (Fig. 17). This was a month of fairly low thundery activity as indicated by meteorological reports, but the reduction in counts is far too great to be ascribed to this diminution in local storms. The Bangkok instrument (Fig. 2) did not actually show any especially low count for August 1967. Therefore the August 1967 CCIR-1 results should be regarded as suspect. There may have been errors in calibration or

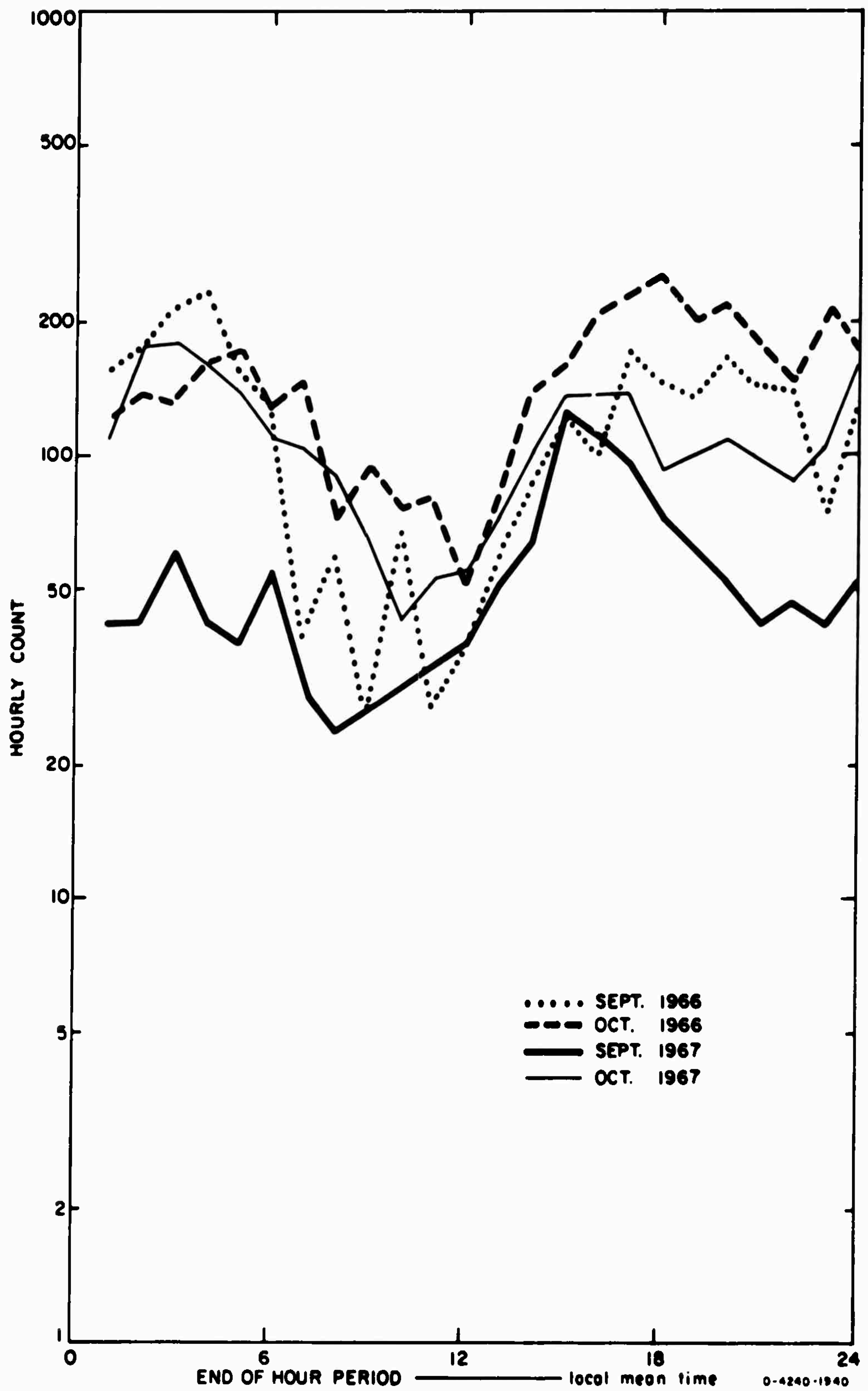


FIG. 15 DIURNAL VARIATION OF CCIR-1 DATA FOR SEPTEMBER AND OCTOBER 1966 AND 1967

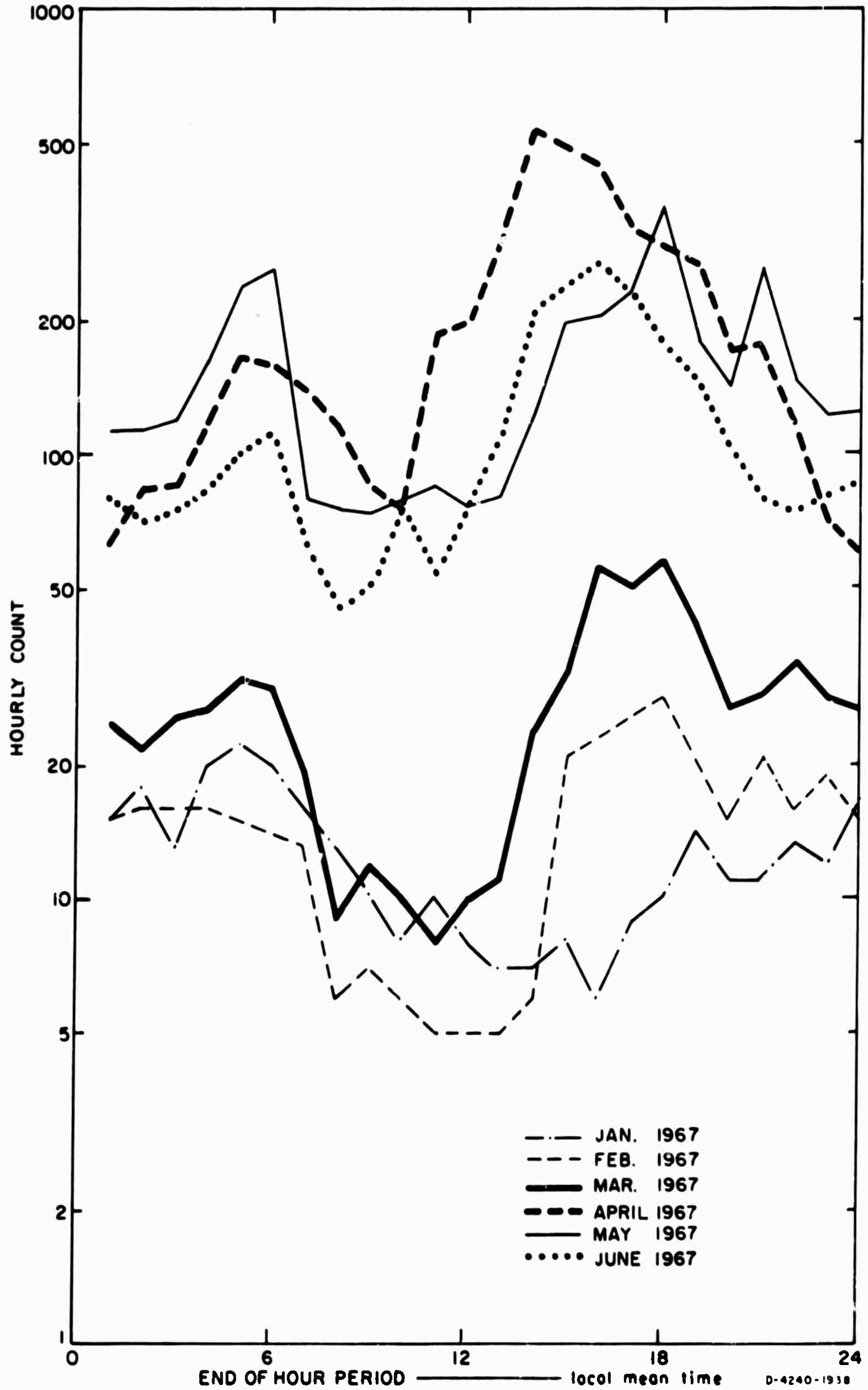


FIG. 16 DIURNAL VARIATION OF CCIR-1 DATA — JANUARY TO JUNE

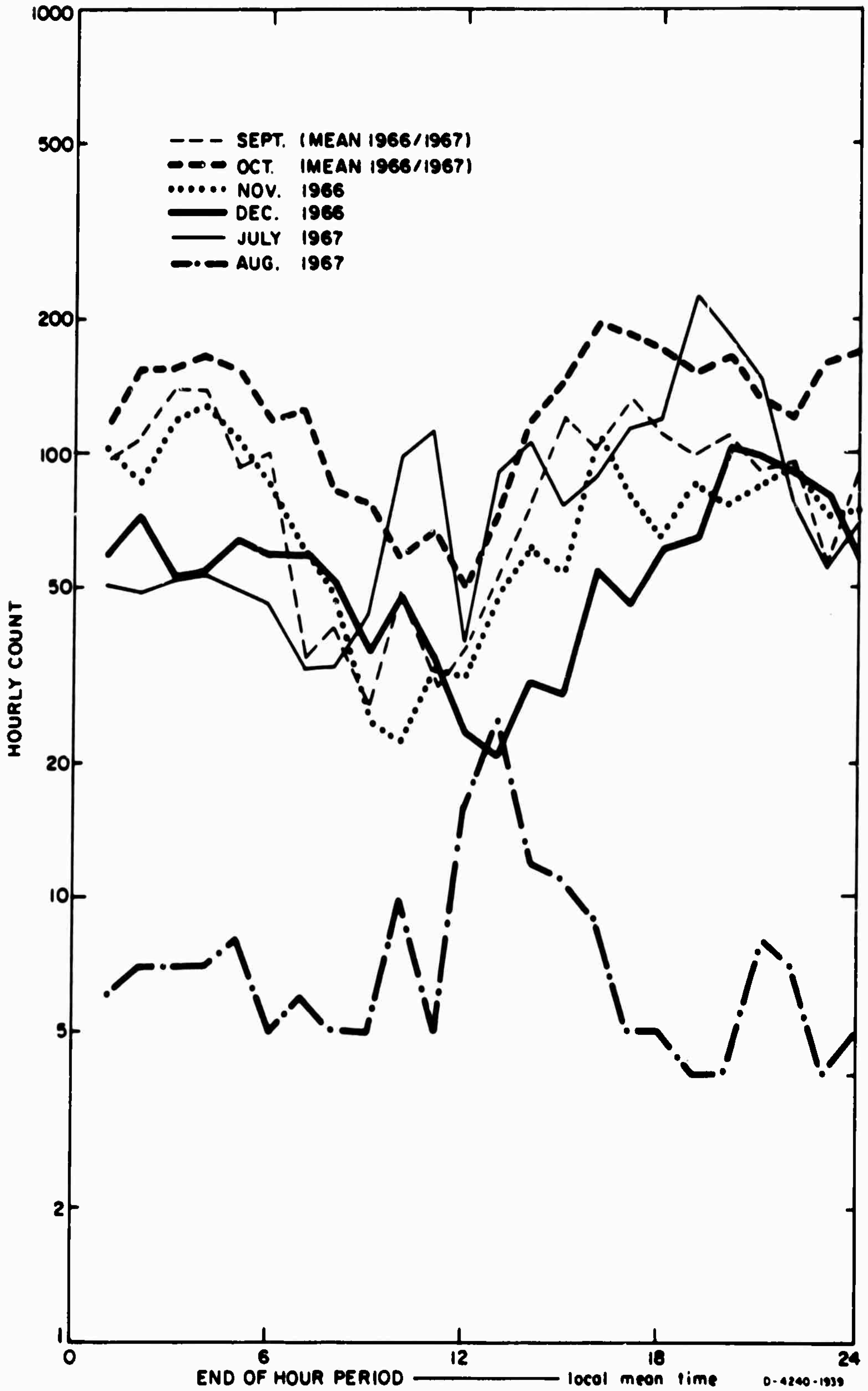


FIG. 17 DIURNAL VARIATION OF CCIR-1 DATA — JULY TO DECEMBER

record scaling; it is perhaps significant that during August 1967 there were several periods when the CCIR-1 counter was inactive.

Figures 16 and 17 indicate a systematic behavior, which, bearing in mind the sensitivity differences between the Bangkok CCIR and the CCIR-1 counter, is quite compatible with that of Figs. 6 and 7. Throughout the year the lowest activity indicated by the CCIR-1 counter tends to occur in the early hours of daylight. In winter the maximum count rates occur at night, but in spring the peak is in the local afternoon; it moves toward the early night hours in late summer and autumn. These features are consistent with the winter results being dominated by VLF impulses from distant storms; these propagate well under night conditions. In spring the influence of local afternoon storms becomes pronounced. As the year progresses, the dual influences of storms occurring later in the day and the change from day to night propagation cause the peak count rate to move toward the evening and night hours. Horner's results[24] for Singapore (Fig. 10) show somewhat similar trends, but in Singapore the actual maximum for all months is in the local afternoon between 1200 and 1800 hours.

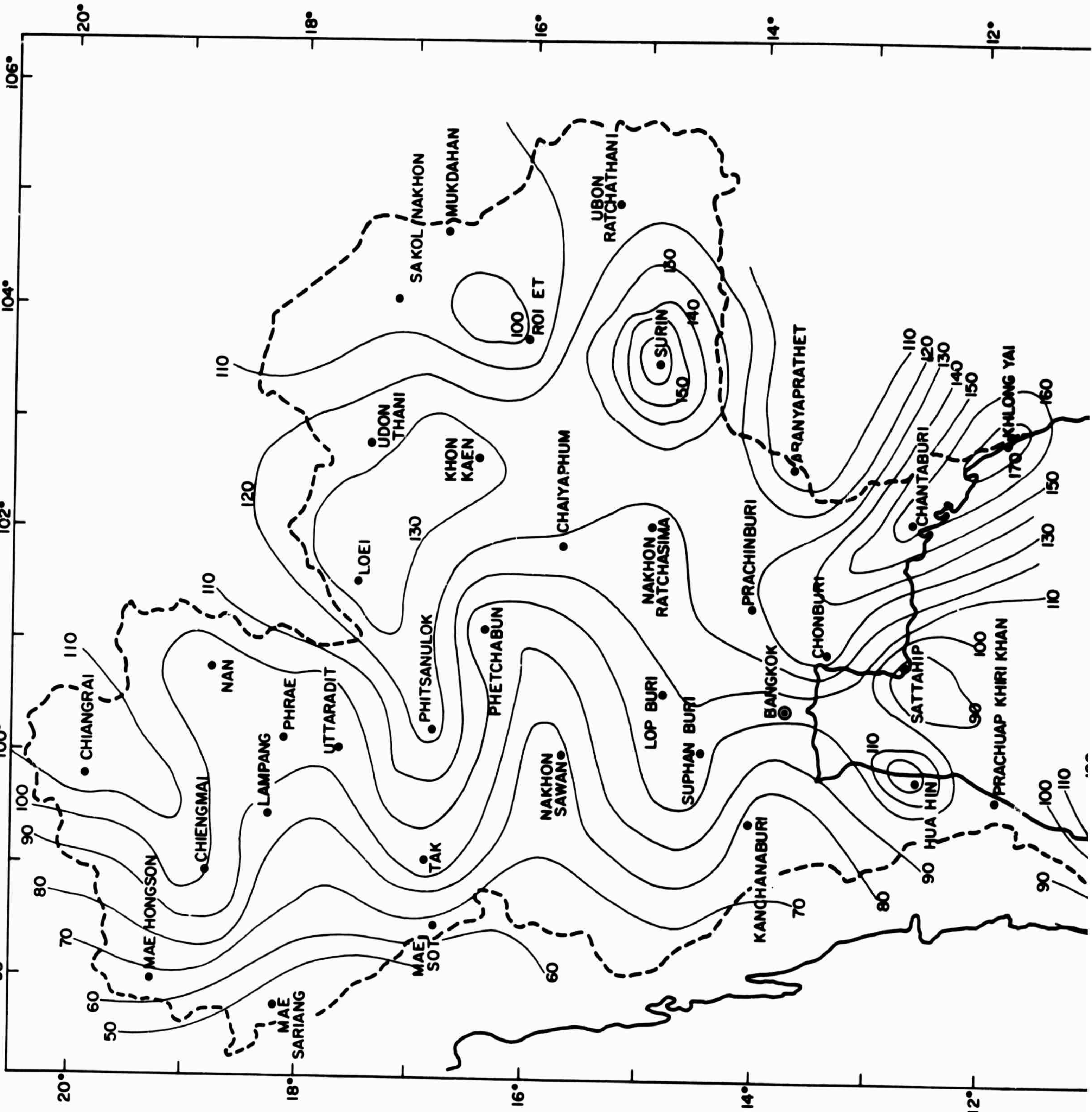
V DISCUSSION AND RECOMMENDATIONS

It was shown on theoretical grounds, in Sec. II, that the range of the ERA counter should be far more precisely defined than that for the CCIR instrument, and that therefore the ERA counter should be the superior indicator of local thunderstorm activity. This distinction results primarily from the different frequency bands at which the two types of counter operate. Several aspects of the experimental data discussed in Sec. III and IV confirm that the ERA design is indeed more definitely responsive than the CCIR counter to thunderstorms in the immediate vicinity of the recording station. This conclusion can be drawn from comparing the broad count distribution of Fig. 4 with the much more steeply peaked distribution of Fig. 12. The efficacy of the ERA design as an on-off indicator is demonstrated by the record of Fig. 11 for Oct. 14-17, 1967; comparison (Fig. 14) with the CCIR-1 counter data for the same period shows conclusively that the CCIR instrument can occasionally indicate quite high count rates even when there are no local thunderstorms. This tendency will be especially marked if--as for the CCIR-1 case--the CCIR design is used at a high sensitivity with a correspondingly large effective range (approximately 100 km). Under these circumstances a pronounced increase in count rate may be due either to the occurrence of a local storm, or to generally intensified activity many hundreds of kilometers away, or even to the change in the propagation characteristics of VLF radio waves from poor to good associated with the day-night transition. The last effect is almost certainly responsible for the winter-month diurnal pattern shown in Figs. 16 and 17.

A gratifying feature of the information obtained with the CCIR counters at Bangkok and Laem Chabang is the general consistency of the estimates for effective range and of the data acquired with the CCIR results previously obtained by Horner[24] at Singapore and at Slough, England. The laws deduced in Sec. III and set out in Eq. (7) imply that the lightning-flash density (discharges per unit area) in a given location, when measured over a substantial period of time (greater than say a month), is proportional to the square of the number of thunderstorm days in the period, T_p^2, for areas of high thunderstorm occurrence, and directly proportional to T_p when the activity is slight. Equation (7) and Fig. 3 suggest an abrupt transition between these two laws. This abrupt transition is of course artificial, resulting from the simple approximate fit made to the available data; more extensive information would have justified attempting a better (more gradual) representation of the transition. It is most interesting to note that there are strong indications, in the present and other work,[24,27,28] that a universal law might be derived relating T_p to counter-measured lightning-flash densities whatever the design of counter employed.

Even when CCIR counter data are considered for a period of as short as a day the agreement between Horner's results and the present information is good. For example, the criteria developed relating the daily count, D_c, to whether the day is reported as a thunderstorm day or not are self-consistent for Singapore, Thailand, and England. So also are the values of D_c corresponding to days of exceptionally violent thundery activity.

As already implied, the monthly and seasonal variations of the Bangkok CCIR counter data are related to the thunderstorm-day meteorological parameter; consequently, following the reverse procedure, if thunderstorm day information is available for any Thailand or tropical station, estimates can be made of lightning-flash-densities. Such information is indeed already established for Thailand. Figure 18 shows the annual isoceraunics derived from the data obtained over the network of meteorological stations in Thailand. In Appendix D, values of the thunderstorm-day parameter per month, T_m, are given for selected stations; these values can be immediately applied to determine lightning-flash-densities at any station for any month using Eqs. (4) to (7) and the analysis of Section III A. The lightning-flash-density information can then be employed to establish the likely degree of enhancement of



CHIANGRAI
NAN
PHRAE
UTTARADIT
LAMPANG
CHIENGMAI
MAE HONGSON
MAE SARIANG
MAE SOT
TAK
PHITSANULOK
PHETCHABUN
LOEI
UDON THANI
KHON KAEN
SAKOL NAKHON
MUKDAHAN
ROI ET
UBON RATCHATHANI
SURIN
CHAIYAPHUM
NAKHON RATCHASIMA
NAKHON SAWAN
LOP BURI
SUPHAN BURI
KANCHANABURI
BANGKOK
PRACHINBURI
ARANYAPRATHET
CHONBURI
SATTAHIP
CHANTABURI
KHLONG YAI
HUA HIN
PRACHUAP KHIRI KHAN
98°
100°
102°
104°
106°
12°
14°
16°
18°
20°

A.

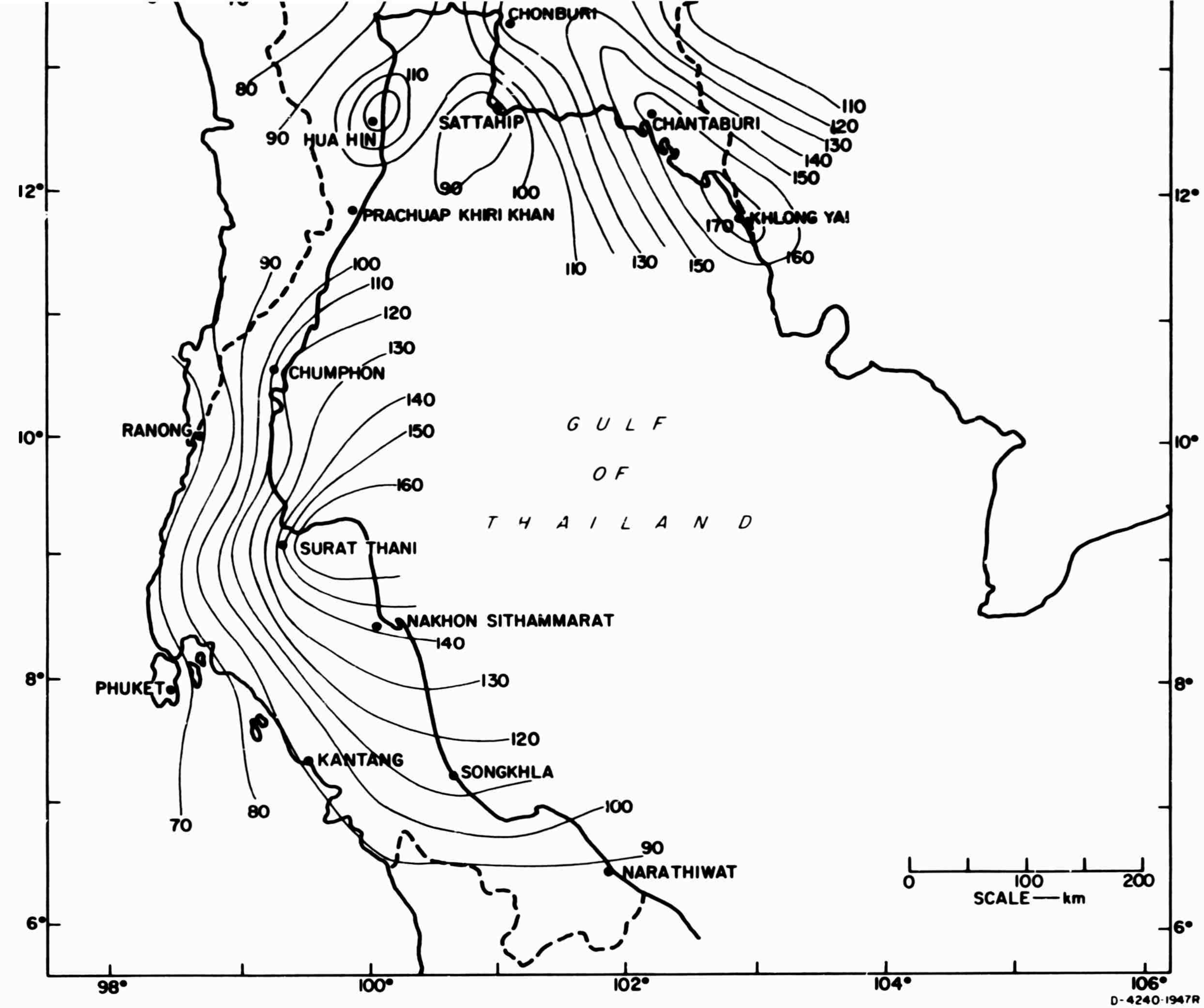


FIG. 18 ANNUAL THUNDERSTORM DAY (Isoceraunic) MAP FOR THAILAND

B.

radio noise due to local storms, employing the relationships indicated by Fig. 13 and in Refs. 2 and 8.

The Bangkok results suggest a diurnal pattern in thunderstorm incidence that is reasonably consistent with meteorological knowledge. Considering the main thundery season, which in Bangkok may be defined as extending from April through October, during the early part of the season peak activity is in the local afternoon. As the season advances, the maximum of activity tends to be increasingly late in the day, and by October occurs in the early evening and night hours. This seasonal trend in diurnal variation is generally supported by the Laem Chabang CCIR-1 data. However, it must be remembered that because of its high sensitivity and large effective range the CCIR-1 counts are not necessarily very closely related to local thunderstorm incidence.

It is demonstrated in Sec. IV that the presence of a local thunderstorm as indicated by the Prentice (ERA) counter increases noise power substantially (Fig. 13). Figures 13 and 14 are for the same time period. Figure 13 shows that the noise power is related to the ERA counts, while Fig. 14 indicates that the ERA counts are in turn related to the CCIR-1 data. It follows that there must be an interrelation between noise power and CCIR-1 counts; this is considered elsewhere.[2]

The recommendations that can be deduced from the results in this report are fairly self-evident. However, specifically, we may suggest the following:

(1) The ERA design of counter is more suitable than the CCIR instrument for investigations in which the main objective is to relate lightning-counter data to local thunderstorm occurrence.

(2) If the main objective is that of (1), the counter employed--whatever its design--should have a fairly short effective range; 20 km might be ideal. With counters of large effective range (high sensitivity), dilution of the results by a background count due to distant storms becomes significant.

(3) The results obtained with the Lightning-Flash Analyzer at Laem Chabang were disappointing. This was for several reasons--some identifiable and some unknown. It

cannot be overstressed that a geophyscial investigation in an unusual environment, such as in the tropics, is more likely to prove profitable when simple well-tried instruments, e.g., the Prentice (ERA) counter, are employed, rather than when new equipment is developed specifically for the investigation.

(4) The reality of certain of the data obtained from the Laem Chabang Lightning-Flash Analyzer is very suspect. It might have been possible to identify and to eliminate some of the sources for the spurious performance if the data had been checked against reasonable expectations as it was acquired; this procedure should always be followed.

Appendix A

EFFECTIVE RANGE OF CCIR LIGHTNING-FLASH COUNTER AT BANGKOK

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Appendix A

EFFECTIVE RANGE OF CCIR LIGHTNING-FLASH COUNTER AT BANGKOK

During the first six months (1964) of counter operation it was estimated, from direct observations of lightning and thunder and from local meteorological and other information, that when a storm was 15 km from the counter site 10% of the lightning flashes generated by the storm were counted; when the storm distances were 10 km and 5 km the corresponding percentages were 25% and 75%.

The CCIR counter is actuated by broad-band VLF impulses. The amplitude distribution of such impulses has been discussed by Arnold and Pierce[30] and Dennis and Pierce.[22] By far the largest VLF signals originate in the return strokes of flashes to earth, but substantial pulses are also created by "K" type recoil streamers; these K changes occur for both cloud-ground and intracloud discharges. The median size of the pulse associated with a K change is perhaps only a tenth as large as the signal radiated during a return stroke. However, perhaps some twenty or thirty K pulses are generated for each complete discharge; this is so whether the flash is within the cloud or to ground. It follows from standard statistical theory that if we assume that the amplitude distribution of the K pulses follows a log-normal law with standard deviation σ (= 6 dB), then the largest K pulse per flash is about 2 σ greater than the median. This is 12 dB, or approximately four times greater than the median K-pulse value, or 0.4 of the size of the typical return-stroke pulse.

Thus when we are analyzing the performance of a CCIR counter, we can neglect the K pulses and need only consider return-stroke effects for cloud-to-ground flashes; however, with intracloud flashes the largest K pulse will be the pulse that is effective in operating the counter.

Suppose we accept that the amplitude distributions of the VLF signals operating the CCIR counter are log-normal with standard deviations of 6 dB* both for flashes to earth (return stroke pulses) and intracloud discharges (largest K pulse). Then, if we adopt the median M_c for the intracloud flashes as our reference level, the median for the return-stroke pulses will be 8 dB greater. Furthermore, most of the literature (see Appendix B) suggests that in a tropical locality such as Bangkok only 10 to 15% of all discharges reach the ground. It is thus possible to construct Fig. A-1. This shows the complete amplitude distribution, for a tropical storm, of the VLF pulses significant in the operation of the CCIR counter. It is noteworthy that the large pulses mostly originate in discharges to earth, while the very small pulses are almost entirely generated in intracloud flashes.

Suppose the threshold setting of the counter is set at τ (corresponding to E_T and V_T), and for the amplitude distribution of Fig. A-1, τ is considered in relation to M_c. Then we can derive Fig. A-2. This shows the fraction of discharges to which the counter responds when the threshold setting is referred to M_c. If the threshold setting corresponds to M_c, then 50% of intracloud flashes and over 90% of discharges to earth operate the counter. However, if the threshold setting is increased by 8 dB it corresponds to the median pulse amplitude, M_E, for a flash to earth; 50% of such discharges are counted, but only some 10% of the intracloud flashes cause the counter to function.

If now we accept that in a tropical thunderstorm 90% of the discharges are of the intracloud type, it can be deduced from Fig. A-2 that for 10% of all flashes to be counted, the trigger setting relative to M_c is at some +9 dB; for 25% and 75% counting efficiencies the corresponding settings are +5 dB and -3.5 dB. As already mentioned,

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* Section II-E suggests that σ is 6 to 8 dB. If the value of 8 dB is selected, the arguments that follow are modified somewhat but the end conclusions are not significantly changed.

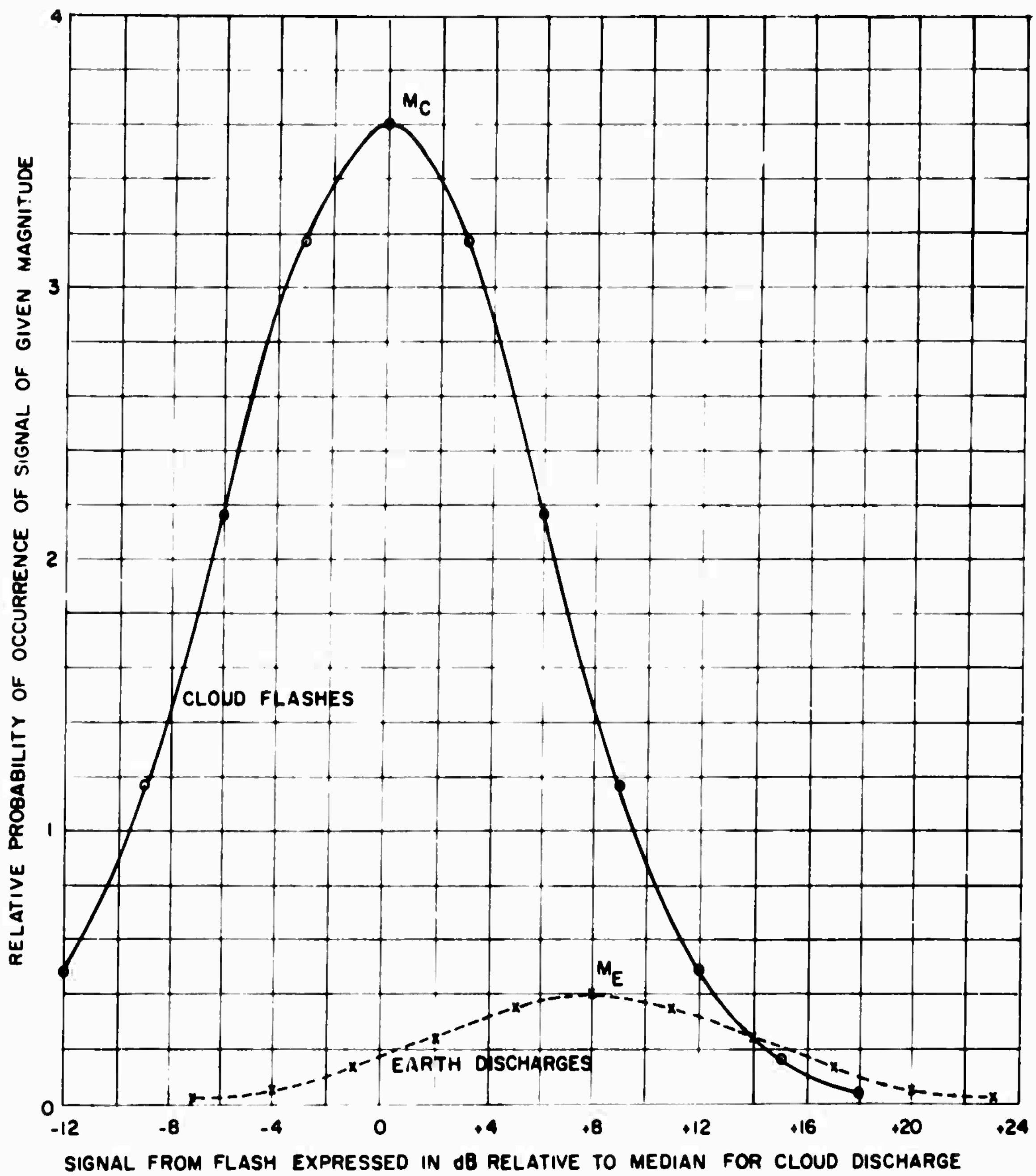

FIG. A-1 AMPLITUDE DISTRIBUTION OF VLF PULSE IN FLASHES IN A TROPICAL STORM

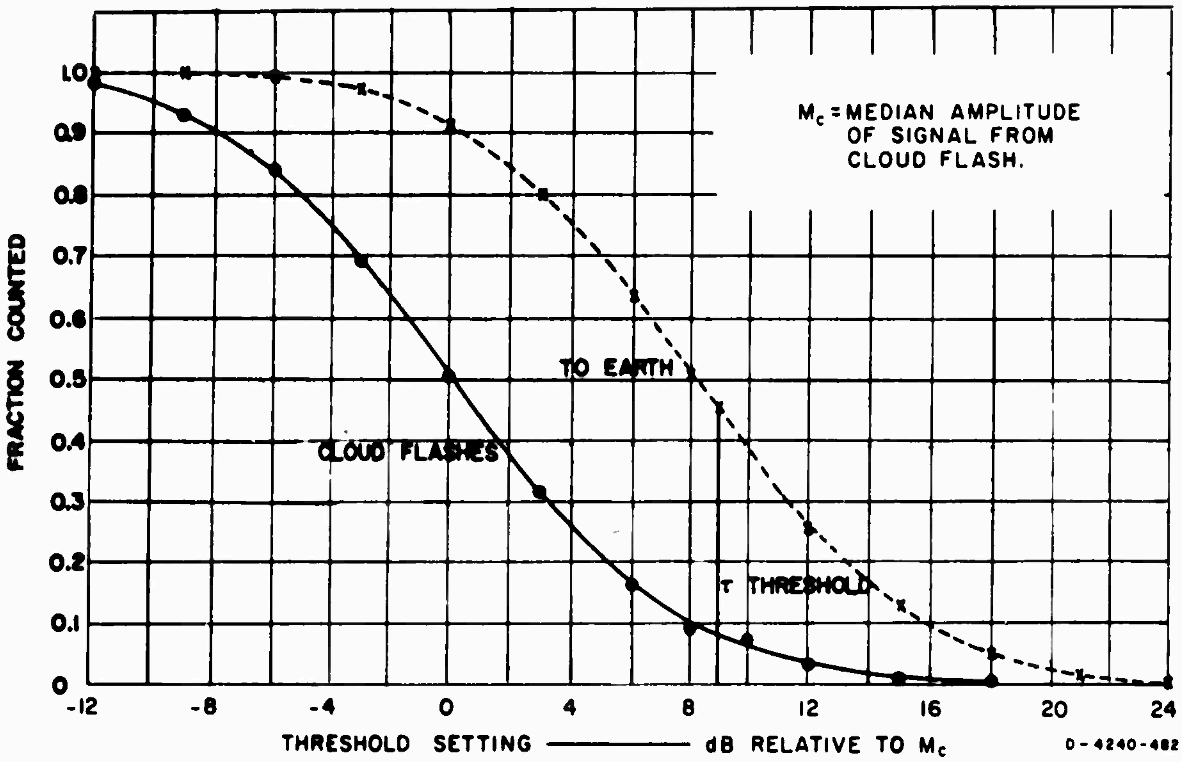

FIG. A-2 FRACTION OF DISCHARGES COUNTED AS A FUNCTION OF THRESHOLD SETTING RELATIVE TO MEDIAN IMPULSE FROM CLOUD FLASHES

visual observations indicate that counting efficiencies of 10%, 25%, and 75% correspond to storms at distances, respectively, of 15, 10, and 5 km. It is interesting to note that if the VLF pulses attenuate during propagation according to an inverse distance law, then relative to the setting for 15 km the respective thresholds for 10 and 5 km are effectively 3.5 and 9 dB down. These values may be compared with those--4 and 12.5 dB--that follow from the analysis above. The agreement at the 10-km distance is good but at 5 km is much less satisfactory. This suggests that departures from the inverse distance law become more pronounced at the closer distances; this is indeed to be anticipated for such influences as finite channel lengths, and near-field effects are then more significant.

Suppose we accept that the triggering level of the Bangkok counter corresponds to registering 10% of the discharges from a storm 15 km away; also that the inverse distance variation applies. These postulations are reasonably consistent with the 25% count from activity at 10 km. Then Fig. A-3 can be constructed. This shows the proportions of intracloud and cloud-to-earth flashes counted, as a function of storm distance from the Bangkok counter site.

The final step is to establish the effective range R. We assume that the thundery activity over the area in the vicinity of the counter is uniform and given by n flashes per square kilometer. Then if N is the number of counts actually registered by the counter we have $N = \pi R^2 n$ as the definition for R. It is convenient to consider the various zonal areas, of width 2 km, defined as lying between the radial distances $(r - 1)$ and $(r + 1)$ from the counter; each zone is of area $4\pi r$ and is centered at distance r. For every specific value of r the fractions--and the numbers--of intracloud and cloud-to-ground flashes that operate the counter can be assessed from Fig. A-3. For example, the zone given by r = 15 km is 60π km^2 in area; it has therefore a total flash activity of $15 \times 4\pi n$ ($= 60\pi n$) with $54\pi n$ of the flashes being intracloud discharges and $6\pi n$ going to earth. Some ~~8~~ 7% of the cloud flashes and about 43% of the discharges to ground operate the counter (Fig. A-3). It follows that the total number of counts from the r = 15 km zone is ~~4.3~~ 3.8πn intracloud flashes plus $2.6\pi n$ flashes to ground. The count contribution is plotted as a function of zone distance in Fig. A-4. Integrating over all distances, the total number of counts is $(28.3) \times 4\pi n = N = \pi R^2 n$. It follows that $R = 10.6 \approx 11$ km.

It can be deduced from the above analysis that the counter actually responds to about 39% of the intracloud flashes and some 80% of the discharges to earth occurring within $r \leq 11$ km. The total proportion for all discharges and $r \leq 11$ km is about 43%. The discharges that are missed are balanced by those originating beyond r = 11 km that are counted; most of these, as can be deduced from Fig. A-4, are flashes to earth. The number of discharges to ground that originate from storms beyond 11 km and are counted is surprisingly large; it exceeds the number from within 11 km by

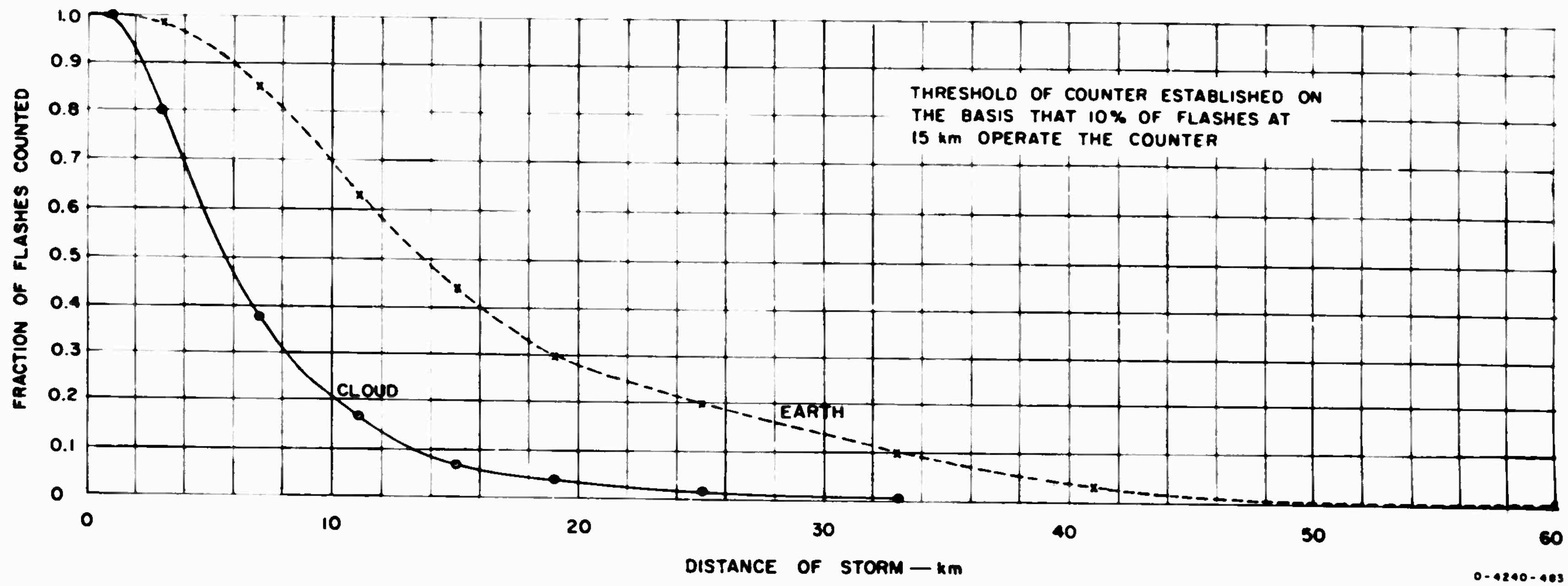

FIG. A-3 FRACTION OF DISCHARGES COUNTED AS A FUNCTION OF DISTANCE OF STORM

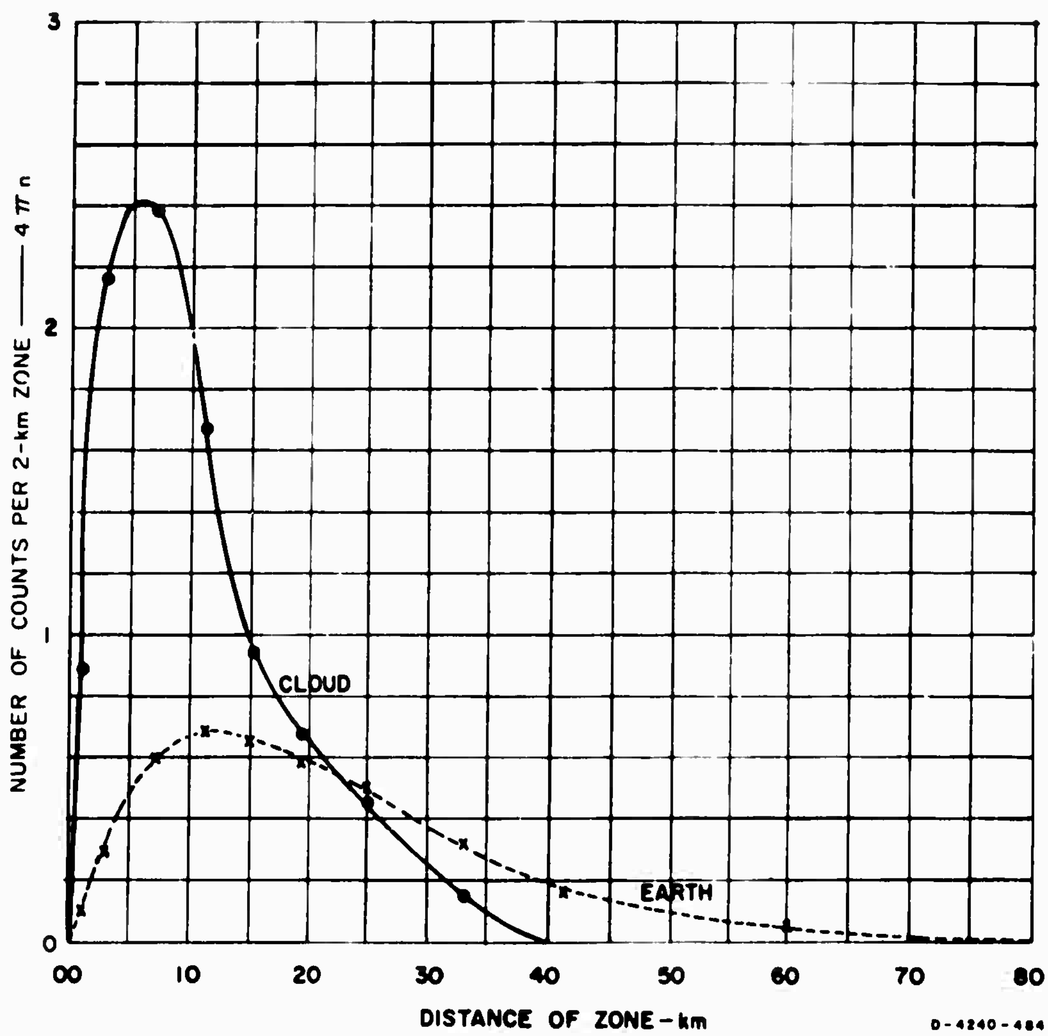

FIG. A-4 COUNT CONTRIBUTION BY ZONAL DISTANCE a factor of over three. For counts of intracloud flashes, however, the number from farther than 11 km is only about 70% of that from less than 11 km. There is an overall bias of the CCIR counter in favor of flashes to earth. Thus, of all the counts registered approximately a third are for cloud-ground discharges, although in actuality the proportion of such flashes occurring in tropical thunderstorms is only some 10% of all discharges.

Appendix B

PROPORTION OF FLASHES TO EARTH

Appendix B

PROPORTION OF FLASHES TO EARTH

It is surprising how little absolute information exists in the literature regarding the proportion, p, of the lightning discharges in a thundercloud that go to ground. The general statement that the fraction increases with increasing latitude is to be found in many references, but there is a remarkable lack of any precise data.

Some results are available in Refs. 13, 25, and 31-41. These data are plotted in Fig. B-1, which shows the proportion of flashes to ground, p, as a function of geographic latitude, λ (North or South). The scatter of the points on Fig. B-1 is considerable, but the general trend is that p increases with increasing λ. The scatter is to be expected since there is much evidence that p does not depend on latitude alone. For example, flashes to earth appear to be relatively more common in mountainous areas than over low-lying plains; thus the location of the observing station, orographically and in altitude, will affect the recorded value of p. Furthermore, the proportion of discharges to ground varies very considerably between individual storms, and can also change drastically during the course of a single storm; in consequence a large number of results are necessary before a sample can be obtained that is adequate statistically to define the long-term average behavior at a specific station.

Two curves are included on Fig. B-1. The equation of the convex curve is

$$p_1 = 0.1 + 0.25 \sin \lambda \quad .$$

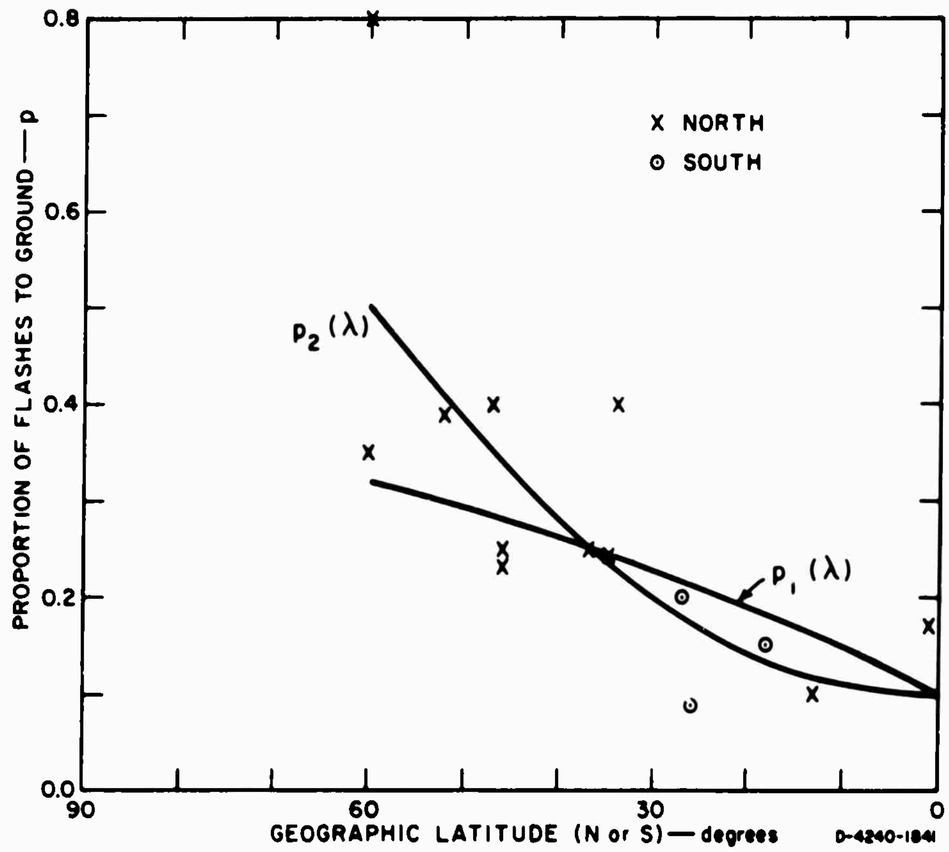

FIG. B-1 PROPORTION OF FLASHES TO GROUND AS A FUNCTION OF LATITUDE

This curve was suggested by Pierce.[42] The concave curve is a rather better fit to the points on Fig. 4. Its equation is

$$p_2 = 0.1 \left\{1+\left(\frac{\lambda}{30}\right)^2\right\}$$

where λ is measured in degrees. Better fits to the results of Fig. B-1 than the two plotted curves can certainly be found. However, any effort to obtain better fits is profitless, since the points of Fig. B-1 are not--as indicated above--to be regarded as absolute data.

Appendix C

FREQUENCY RESPONSE OF LAEM CHABANG
LIGHTNING-FLASH ANALYZER SYSTEMS

Appendix C

FREQUENCY RESPONSE OF LAEM CHABANG LIGHTNING-FLASH-ANALYZER SYSTEMS

The intended design of the analyzer incorporated two filters feeding ERA-type and CCIR-type counters respectively.[29] The nominal characteristics of the ERA bandpass filter unit included a center on 500 Hz, with the 3-dB-down points at 100 Hz and 2500 Hz; actual measurements gave a center at 500 Hz, with 3-dB points at 107 Hz and 2.05 kHz. The CCIR filter was nominally centered at 10 kHz and down 3 dB at 2 kHz and 50 kHz; the measurements showed the center at 6.9 kHz with 3-dB points at 1.95 and 27 kHz.

Most unfortunately, a low-value (20-kΩ) resistor was introduced across the antenna. The reasons for its introduction seem obscure. It does not appear to have been realized that the shorting resistor would act, in conjunction with the antenna capacitance, as a high-pass filter through which the lightning signals must traverse before they enter the band-pass filters of the analyzers. The combination of the initial high-pass filter and of the subsequent band-pass filters obviously makes the overall frequency response far different from that originally intended. It is the purpose of this Appendix to evaluate this overall frequency response and hence to estimate to exactly which parts of the lightning signal the counters are responding.

We will assume that the antenna circuit is equivalently as in Fig. C-1. The lightning signal S feeds through 100 pF--the equivalent antenna generating capacitance--to produce a voltage V across the 20-kΩ resistor. Tests show that the loss in this antenna stage is given by the following table.

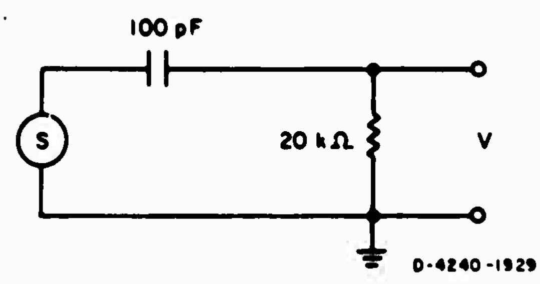

FIG. C-1 EQUIVALENT ANTENNA CIRCUIT
(Actual Values)

Table C-1

MEASURED LOSS IN ANTENNA STAGE
OF LAEM CHABANG LIGHTNING-FLASH ANALYZER

Frequency (kHz)	Loss (dB)	Frequency (kHz)	Loss (dB)
0.1	58	5	24
0.5	44	10	19
1	38	50	9

More experimental tests showed that the subsequent cathode follower stage did not introduce any further gains or losses.

The equivalent antenna circuit is a simple resistance-capacitance network (Fig. C-2) for which, with angular frequency, ω,

$$\frac{V}{S} = A \exp(j\theta)$$

where A, the amplitude, is $\omega CR/\sqrt{1 + \omega^2 C^2 R^2}$ and θ, the phase angle, is given by $\tan\theta = 1/\omega CR$. For the antenna circuit as employed we have $CR = 2 \times 10^{-6}$ s, and the Table C-2 for A.

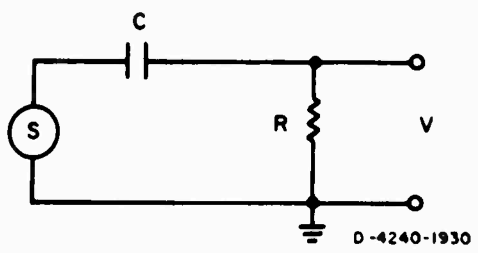

FIG. C-2 EQUIVALENT ANTENNA CIRCUIT (Generalized)

Table C-2

CALCULATED LOSS IN ANTENNA STAGE
OF LAEM CHABANG LIGHTNING-FLASH ANALYZER

Frequency (kHz)	ωCR	A	Log A	dB down (20 log A)
0.1	$4\pi \cdot 10^{-4}$			58
0.5	$2\pi \cdot 10^{-3}$			44
1	$4\pi \cdot 10^{-3}$			38
5	$2\pi \cdot 10^{-2}$	0.06272	$\bar{2}.7974$	24
10	$4\pi \cdot 10^{-2}$	0.1247	$\bar{1}.0959$	18
50	$2\pi \cdot 10^{-1}$	0.3161	$\bar{1}.4998$	10
100	$4\pi \cdot 10^{-1}$	0.7810	$\bar{1}.8927$	2
500	2π	0.9874	$\bar{1}.9945$	0.1
1000	4π	0.9967	$\bar{1}.9986$	0.03

Note that this confirms the experimental measurements of Table C-1 very well.

The frequency-response characteristics of the two bandpass filters--ERA and CCIR--are not readily calculable. As far as can be seen from Fig. 29 in Ref. 29, both filters have the circuit form shown in Fig. C-3.

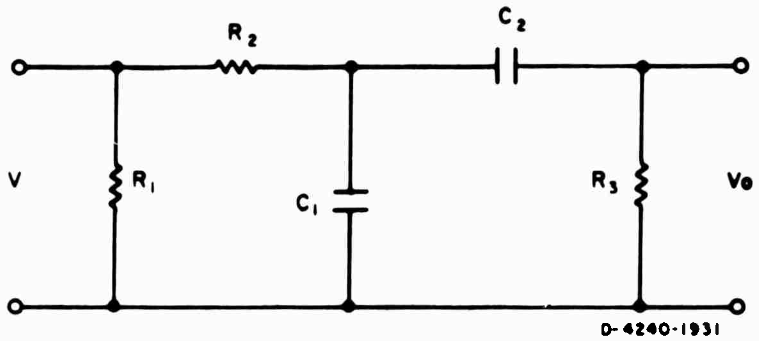

FIG. C-3 ERA AND CCIR FILTER CIRCUITS (Generalized)

The components R_1, R_2, C_1, C_2 are single resistors and capacitors, but for both filters R_3 is a complicated chain of resistors upon which different tappings can be made. However, these tappings only influence sensitivity; they do not affect the frequency response, which is entirely represented in the frequency dependency of V_o/V. For both filters R_1 is large compared with 20 kΩ; its influence on the overall frequency-response characteristic is therefore negligible.

For the ERA filter the values of the filter elements are approximately R_2 = 51 kΩ, C_1 = 1300 pF, C_2 = 1200 pF, and R_3 = 1600 kΩ. The network analysis yields:

$$\frac{V_o}{V} = \left[\frac{j\omega C_2 R_3}{j\omega(C_2R_2 + C_2R_3 + C_1R_2) + 1 - \omega^2 C_1C_2R_2R_3} \right] .$$

From this the proportionate losses as a function of frequency produced by the filter can be calculated. The analysis is laborious but gives Table C-3.

Table C-3

CALCULATED RESPONSE OF ERA-TYPE FILTER

Frequency (kHz)	dB down	Frequency (kHz)	dB down
0.1	2.4	50	26
0.5	0.4	100	32
1	0.8	500	46
5	7	1000	52
10	12		

The results of this theoretical analysis are in fair agreement with the experimental measurements (3 dB down at 107 Hz and 2.05 kHz).

For the CCIR filter the elements have the approximate values $R_2 = 5$ kΩ, $C_1 = 300$ pF, $C_2 = 600$ pF, $R_3 = 100$ kΩ. The analysis for the filter losses as a function of frequency yields the values given in Table C-4.

Table C-4

CALCULATED RESPONSE OF CCIR-TYPE FILTER

Frequency (kHz)	dB down	Frequency (kHz)	dB down
0.1	28	50	1.3
0.5	15	100	3
1	9	500	14
5	1.5	1000	20
10	0.8		

The calculations for this filter do not agree very well with the measurements (center at 7 kHz with 3-dB points at 2 and 27 kHz).

The responses of the two filters and of the antenna circuit are plotted as smooth curves in Fig. C-4. (Note that the point at 50 kHz for the antenna curve seems in error.) In Fig. C-5 the responses of the two combinations--antenna + ERA and antenna + CCIR are shown.*

* An approximate experimental check was made of these curves by using a dummy antenna capacitance, feeding it with a generator and measuring overall system behavior.

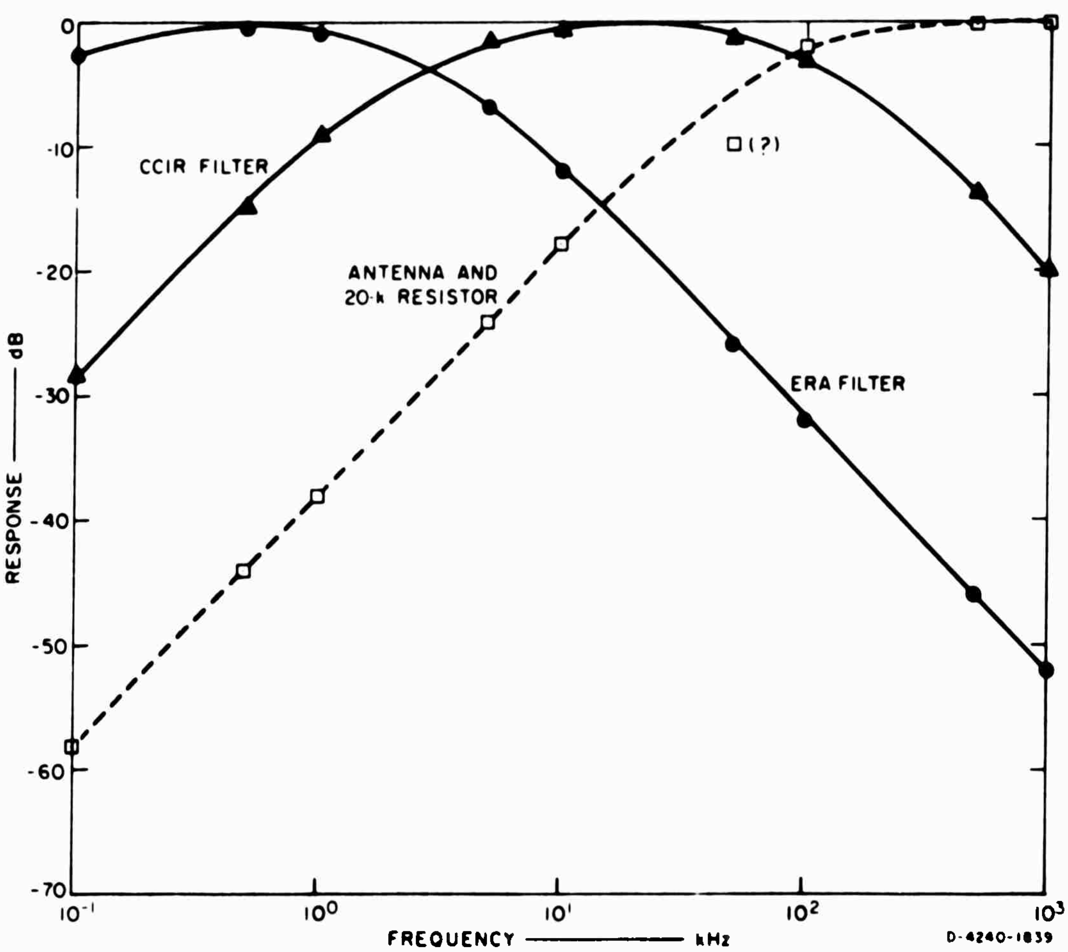

FIG. C-4 FREQUENCY RESPONSE OF ANTENNA AND ERA–CCIR FILTER CIRCUITS

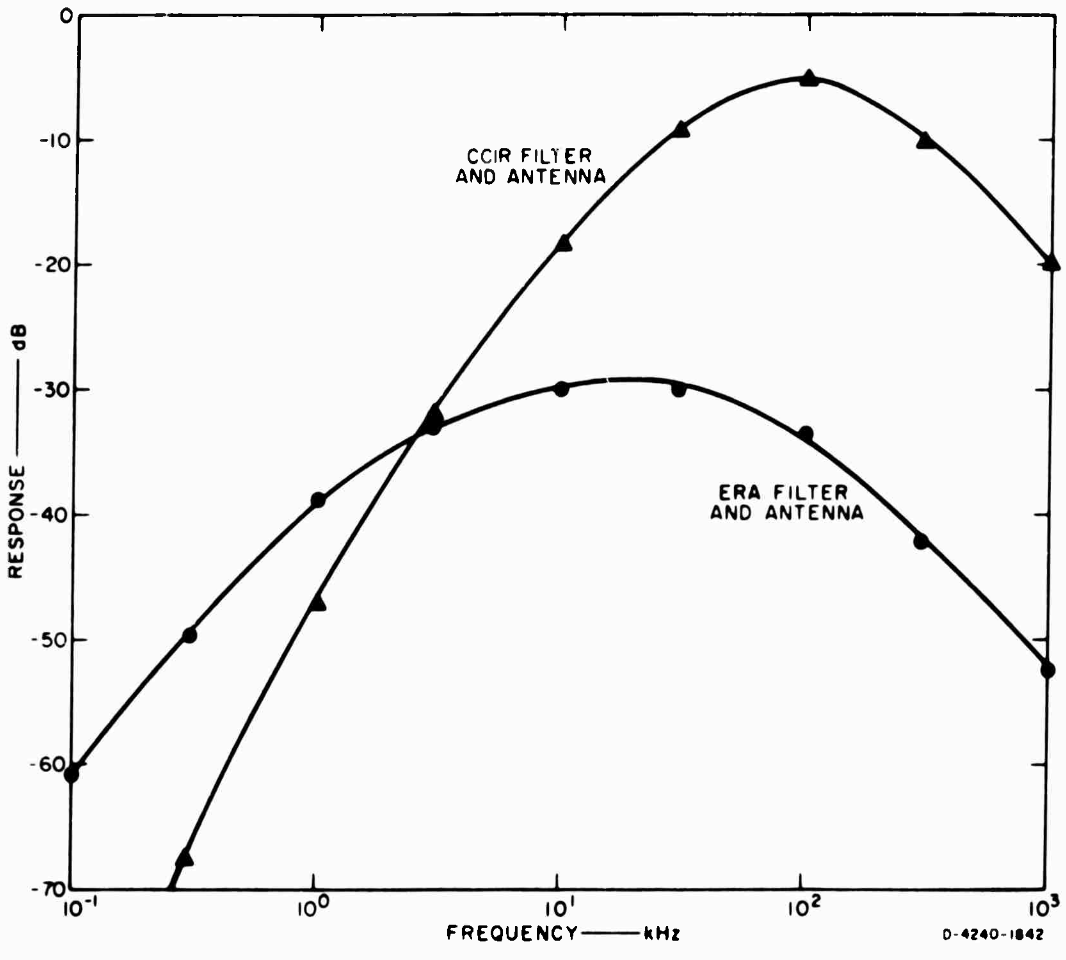

FIG. C-5 FREQUENCY RESPONSE OF ANTENNA AND ERA-CCIR FILTER CIRCUITS COMBINED

Note that the ERA combination gives a fairly flat response over much of the spectrum with the peak in the VLF and low LF bands from 3 to 100 kHz; this response, strangely enough, is not very dissimilar to that of the original CCIR filter (Fig. C-4). The CCIR combination response is sharper and greatest in the LF band (30 to 300 kHz). Note that the overall attenuation is much greater for the ERA combination than it is for the CCIR arrangement.

Lightning emits signals at all frequencies. In order to determine to which part of the lightning-signal spectrum the combinations of Fig. C-5 are responding, it is necessary to make some estimate of the incident signal spectrum. Unfortunately, this signal changes rapidly with distance close to the source; this is not primarily due to propagation but because of the changing dominance between near- and far-field components. The spectrum in Fig. C-6 is an approximation that probably applies at distances of 10 to 50 km; the uncertainties are greatest below some 3 kHz. Combining the curves of Fig. C-5 and the lightning spectrum graph of Fig. C-3 gives the two Signal-Antenna-Filter curves of Fig. C-6. These show that the overall response of the CCIR System is to the frequency band of some 10 to 50 kHz; that of the ERA System is considerably diminished and is centered predominantly on 3 to 20 kHz. In each case the counters will be activated by radiation fields (inverse distance relation); this is, of course, quite contrary to the function originally intended for the ERA system.

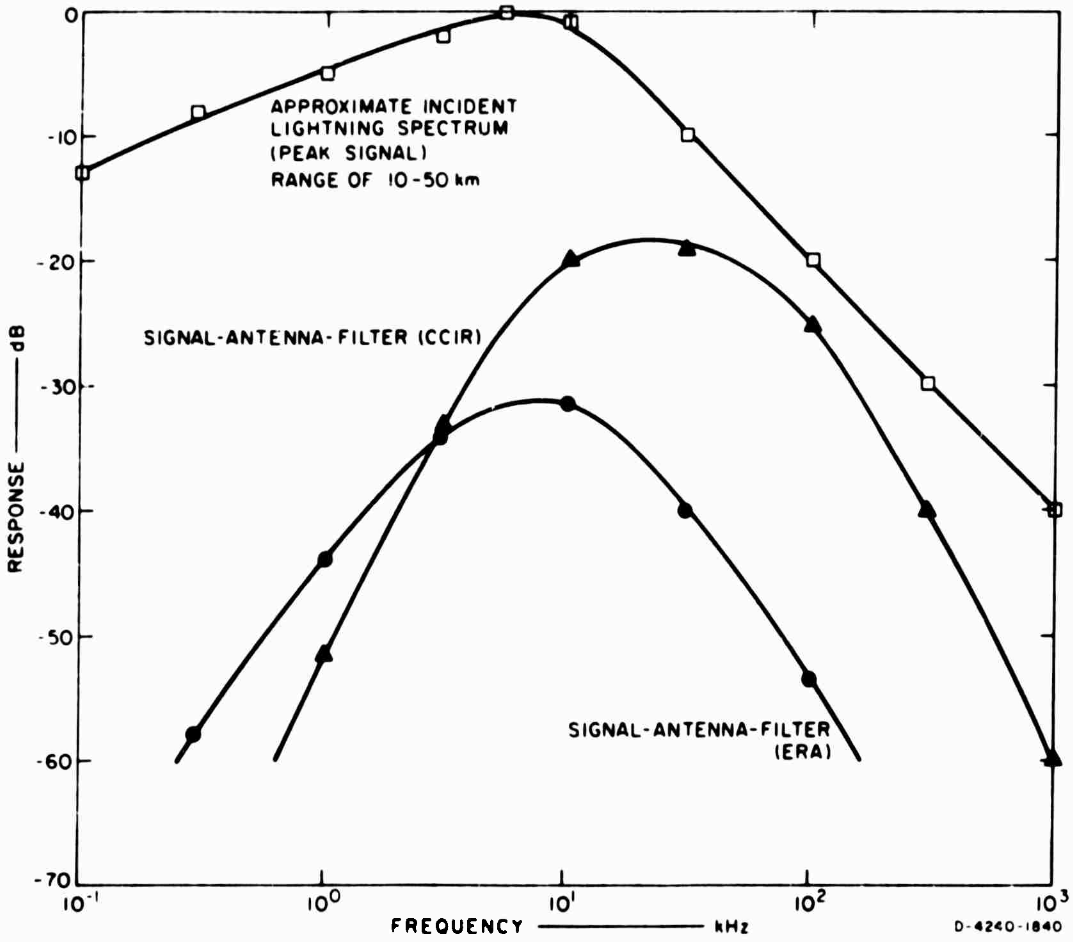

FIG. C-6 COMBINED RESPONSE OF ANTENNA AND FILTER (ERA AND CCIR) TO LIGHTNING SIGNAL

Appendix D

MONTHLY THUNDERSTORM-DAY DATA FOR SELECTED SITES IN THAILAND

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Appendix D

MONTHLY THUNDERSTORM-DAY DATA FOR SELECTED SITES IN THAILAND

The monthly and annual thunderstorm-day data of Table D-1 were made available 20 June 1958 (2501 B.E.) by C. Kanisthasut (compiler), K. Sukhapinda (checker), and S. Thunvanont (printer) of the Climatological Division, Meteorological Department, Royal Thai Navy, Bangkok, Thailand. The data cover about ten years (nominally 1948 through 1957). In most cases, the annual data agree with the data plotted on the isoceraunic map of Fig. 18. The minor discrepancies probably are due to a difference in the period of observation. While the periods of the data in Table D-1 are indicated, the period (or periods) represented in the map is unknown to the author.

These data were accompanied by a brief discussion of certain meteorological characteristics associated with thunderstorms in Thailand. This discussion is reproduced below.

Table D-1

MONTHLY FREQUENCY OF THUNDERSTORM DAYS (T_m)

STATION	LAT. N	LON. E	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEPT.	OCT.	NOV.	DEC.	TOTAL	PERIOD
Chiangrai	19°55'	99°50'	0.3	1.7	5.1	9.5	21.5	17.4	16.3	16.8	15.7	7.9	1.6	0.1	113.9	1948 - 1957
Chiengmai	18 47	98 59	0.3	1.6	3.6	9.5	23.9	14.5	12.2	16.7	17.0	10.7	2.4	0.0	112.4	1948 - 1957
Nan	18 47	100 47	0.4	1.2	5.2	10.0	19.0	8.8	11.9	12.7	13.1	7.7	1.1	0.0	91.1	1948 - 1957
Lampang	18 15	99 30	0.0	1.0	5.2	8.4	15.2	9.1	11.1	11.3	11.9	6.5	0.7	0.0	80.4	1948 - 1957
Mae Sariang	18 10	97 50	0.0	0.8	1.9	4.7	11.2	3.2	2.5	3.6	7.1	8.2	2.3	0.0	45.5	1948 - 1957
Mae Hongson	19 18	97 50	0.4	0.5	2.5	9.3	14.7	5.1	4.3	5.3	10.4	8.6	3.2	0.2	64.5	1948 - 1957
Phrae	18 10	100 08	0.0	0.7	4.7	11.7	18.3	11.7	10.3	14.3	13.3	6.7	1.3	0.0	93.0	1955 - 1957
Uttaradit	17 37	100 08	0.1	1.2	4.7	8.7	17.2	11.5	9.7	12.7	14.4	7.6	1.5	0.0	89.3	1948 - 1957
Mae Sot	16 40	98 33	0.3	1.9	3.9	9.9	15.1	7.0	3.6	4.4	8.8	8.5	2.6	0.0	66.0	1948 - 1957
Tak	16 51	99 07	0.0	2.5	5.0	10.5	19.0	12.0	11.3	8.8	11.5	7.8	2.0	0.0	90.4	1954 - 1957
Phitsanulok	16 50	100 16	0.3	2.3	7.6	12.0	21.7	18.6	15.5	14.6	17.5	13.2	2.3	0.2	125.8	1948 - 1957
Phetchabun	16 25	101 08	1.1	2.3	10.5	15.1	21.9	10.3	10.5	7.9	12.1	6.3	1.7	0.0	99.7	1950 - 1957
Nakhon Sawan	15 48	100 10	0.1	1.6	5.5	8.6	14.6	8.9	10.9	7.6	9.9	7.8	1.4	0.1	77.0	1948 - 1957
Lop Buri	14 48	100 37	0.4	3.5	8.9	13.0	17.0	11.9	11.8	10.3	13.9	9.6	2.7	0.2	103.2	1948 - 1957
Kanchanaburi	14 01	99 32	0.1	2.1	7.7	10.9	15.0	5.5	7.4	5.9	10.1	8.6	2.4	0.0	75.7	1948 - 1957
Suphan Buri	14 30	100 10	0.6	1.6	7.8	10.5	18.5	8.1	13.1	13.2	13.8	11.1	2.7	0.0	101.0	1948 - 1957
Bangkok	13 44	100 30	0.2	2.2	6.0	11.2	17.3	11.7	12.8	11.2	14.0	12.1	4.4	0.3	103.4	1948 - 1957
Chonburi	13 30	101 05	1.1	5.8	14.9	19.3	19.2	12.2	14.3	12.5	15.0	15.6	7.1	0.3	137.3	1948 - 1957
Sattahip	12 39	100 53	0.7	3.6	9.0	13.9	14.2	5.3	6.7	5.4	9.0	13.2	6.3	0.2	87.5	1948 - 1957
Chantaburi	12 37	102 07	1.8	7.6	17.5	20.3	25.6	15.4	19.6	15.4	16.7	16.8	6.3	0.5	163.5	1948 - 1957
Khlong Yai	11 47	102 53	4.4	9.4	20.3	25.8	25.8	17.9	15.4	13.7	11.9	19.0	10.5	0.8	174.7	1948 - 1957
Prachinburi	14 10	101 10	0.9	4.2	13.6	18.3	21.6	13.1	14.1	12.4	14.8	9.5	2.9	0.1	125.5	1948 - 1957
Aranyaprathet	13 42	102 35	0.7	4.3	11.1	17.5	19.2	11.4	10.8	8.9	8.9	9.4	2.9	0.1	105.2	1948 - 1957
Loei	17 32	101 30	0.0	2.3	12.8	17.8	27.3	18.3	18.5	17.3	16.0	5.3	0.0	0.0	135.6	1954 - 1957
Udon Thani	17 26	102 46	0.3	3.3	6.8	15.2	23.1	17.7	18.4	16.4	16.4	5.1	1.8	0.4	124.9	1948 - 1957
Sakol Nakhon	17 10	104 09	0.2	1.8	7.0	13.3	22.5	15.5	15.3	15.0	11.7	3.7	0.4	0.0	106.4	1948 - 1957
Khon Kaen	16 20	102 51	0.4	2.9	9.2	15.1	23.0	17.0	19.2	6.7	7.4	7.9	0.9	0.0	110.0	1948 - 1957
Mukdahan	16 33	104 44	0.1	1.4	5.6	13.8	21.1	11.7	16.8	15.2	14.3	3.8	0.6	0.0	107.4	1948 - 1957
Roi Et	16 03	103 41	0.0	2.3	7.0	11.9	19.4	12.1	13.1	10.9	14.4	7.5	1.4	0.0	100.0	1948 - 1957
Chaiyaphum	15 45	102 02	2.0	2.0	8.0	9.0	20.0	12.0	13.0	9.5	12.5	4.5	0.5	0.0	93.0	1956 - 1957
Nakhon Ratchasima	14 58	102 07	0.8	3.7	11.7	17.3	22.5	12.5	12.7	10.2	13.9	9.2	1.3	0.0	115.8	1948 - 1957
Surin	14 53	103 29	0.6	3.6	11.9	19.0	26.0	21.3	22.2	20.4	20.3	13.6	2.7	0.0	161.6	1948 - 1957
Ubon Ratchathani	15 15	104 53	0.0	1.4	6.7	13.7	22.2	16.4	16.9	14.8	13.4	7.3	2.9	0.0	115.7	1948 - 1957
Hua Hin	12 34	99 48	0.8	3.1	8.1	15.6	23.7	11.8	12.2	12.4	14.9	18.1	6.7	0.2	127.6	1948 - 1957
Prachuap Khiri Khan	11 48	99 48	1.0	2.5	7.8	14.8	21.7	10.8	7.8	6.7	8.5	12.4	5.4	0.5	99.9	1948 - 1957
Chumphon	10 27	99 15	2.3	3.8	11.2	19.4	23.3	10.8	10.5	6.1	10.0	14.8	9.6	3.4	125.2	1948 - 1957
Ban Don (Surat Thani)	09 08	99 18	3.6	5.4	12.4	24.7	25.3	14.9	18.8	13.7	13.9	18.7	11.6	3.2	166.2	1948 - 1957
Nakhon Sithammarat	08 25	99 58	2.6	2.3	5.4	17.9	23.6	11.1	15.0	11.5	12.5	17.6	10.3	5.8	135.6	1948 - 1949
Songkhla	07 11	100 37	1.0	1.3	3.0	15.0	21.1	11.6	15.3	12.6	13.7	13.2	8.5	2.1	118.4	1948 - 1957
Narathiwat	06 26	101 50	0.1	1.0	2.2	7.7	14.9	12.1	11.5	11.5	10.7	6.4	3.6	0.8	82.5	1948 - 1957
Ranong	09 58	98 38	1.0	1.9	8.5	16.9	11.3	5.7	4.6	5.0	4.1	7.6	4.5	0.6	71.7	1948 - 1957
Phuket	07 58	98 24	1.8	3.7	9.9	15.1	12.1	4.1	4.6	2.6	2.1	6.6	4.9	2.1	69.6	1948 - 1957
Kantang	07 20	99 30	2.0	4.0	9.8	20.3	15.2	5.3	6.6	4.8	5.1	10.1	6.4	2.1	91.7	1949 - 1957

DISTRIBUTION OF THUNDERSTORM DAYS IN THAILAND

1. By international agreement, a "Thunderstorm Day" is defined as a local calendar day on which thunder is heard. A thunderstorm day is recorded as such regardless of the actual number of thunderstorms occurring on that day. Lightning without thunder is not recorded as a thunderstorm.

2. The regions most subject to thunderstorms are: localities between Meoi and Khon Kaen, Nakhon Ratchasima and Ubon Ratchathani, Chanthaburi and Khlong Yai and the West Coast of the Gulf Of Thailand between Chumpon and Songkhla. Other localities where they are fairly frequent are: Chiangrai, Phitsanuloke, Chaiyaphum, Nakhon Ratchasima to Bangkok and Hua Hin. The maximum monthly frequencies occur in April and May as well as September to mid-October.

3. The types of thunderstorm are: Heat or Airmass types are generally the case in April and May. While frontal types are significant in October. While in the other months orographic thunderstorms are usually the case. The intensity of thunderstorms is mostly in the period of April and May and in October. By intensity here we mean thunderstorms accompanied by violent thunders and bolts as well as great wind velocities with some structural damages. For extreme wind velocities in violent thunderstorms please see Table V.* Duration in a severe thunderstorm lasts from 30 to 180 minutes. The extent of the storms from estimation is from a small area of about 1-2 km^2 to 3-5 km^2 which depends on the nature of the locality. In open or coastal region, the extent is great. While in the city area is contrariwise. It is interesting to note that the periods of thunderstorm activity usually are associated with periods of unsteady winds preceding the events.

4. The times of maximum occurrence are mainly in the afternoon and evening, that is, between 3 to 6 p.m. This is applied to the Heat and Orographic types. While the minimum is between midnight to 11 a.m. Those occurring in the night and towards day-break are generally of frontal type.

Climatological Division,
Meteorological Department,
Royal Thai Navy,
Bangkok, June 20, B.E. 2501 (1958).

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* It should be noted that Table V (on wind velocities) mentioned here is not reproduced in this report.

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UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Stanford Research Institute Menlo Park, California 94025	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP N/A

3. REPORT TITLE

THE COUNTING OF LIGHTNING FLASHES

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Special Technical Report 49

5. AUTHOR(S) (First name, middle initial, last name)

Edward T. Pierce

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
June 1968	110	42

8a. CONTRACT OR GRANT NO. Contract DA 36-039 AMC-00040(E) b. PROJECT NO. Order No. 5384-PM-63-91 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) Special Technical Report 49 SRI Project 4240 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

Distribution of this document is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Advanced Research Projects Agency Washington, D.C.

13. ABSTRACT

The principles involved in using lightning-flash counters are first discussed, with especial reference to the ERA and CCIR types of counter. The concept of an effective range is introduced, and it is shown how the value obtained for the effective range is influenced by counter sensitivity and by the amplitude distribution of the lightning-generated signals at the thunderstorm source.

The results obtained at two sites in Thailand with ERA and CCIR counters are presented, analyzed, and compared with data for Singapore. It is established that during months of high thunderstorm incidence the lightning-flash density is proportional to the square of the well-known thunderstorm-day parameter; for low-activity months, the proportionality is direct. The transition between the two laws occurs when the number of thunderstorm days per month, T_m, is about three. Over most of Thailand T_m always exceeds three except during the months of December through February.

Seasonal and diurnal variational patterns in lightning incidence are derived. Monthly changes are related, as indicated above, to the T_m statistic. As regards diurnal variation, from March to June thunderstorms tend to break out in the local afternoon; later in the year the peak activity moves to the early evening and night hours.

It is demonstrated that the occurrence of a nearby thunderstorm increases received atmospheric noise power—for example, by some 10 to 20 dB at MF.

Finally, comparisons of the data from the ERA and CCIR counters demonstrate that the former design is superior in precision as an indicator of local thundery activity. The CCIR type of counter has an inherent propensity to respond to the larger impulses generated in distant thunderstorms; this effect becomes increasingly pronounced as the counter sensitivity is increased.

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S/N 0101-807-6801

UNCLASSIFIED

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Lightning Flash Counter						
ERA						
CCIR						
Range of lightning flash counter						
Radio Noise						
Tropical Thunderstorms						
Thunderstorm Climatology						
Thailand						
SEACORE						

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